Tang et al. BMC Musculoskeletal Disorders (2025) 26:336
https://doi.org/10.1186/s12891-025-08575-2

BMC Musculoskeletal Disorders

RESEARCH Open Access

# Establishment and validation of a prognostic nomogram for periprosthetic femoral fracture after total hip replacement surgery

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## Abstract

**Background** In recent years, with the gaining popularity and wide application of total hip arthroplasty (THA), the incidence rate of periprosthetic femoral fractures (PFF) has increased. The treatment of PFF is difficult and has many related complications. Herein, we aimed to construct a nomogram model to predict occurrence of PFF after THA, in order to identify high-risk populations.

**Methods** In this retrospective analysis, we selected 2,528 patients who underwent THA at Wuhan Fourth Hospital from January 2014 to August 2022. Patients were randomly divided into a training cohort (*n* = 1,770) and an internal validation cohort (*n* = 758) in a 7:3 ratio. Least Absolute Shrinkage and Selection Operator (LASSO) algorithm and logistic regression analysis were used to perform feature analysis and convert them into a nomogram model. The model was externally validated in 1,383 THA patients at Renmin Hospital of Wuhan University.

**Results** Six independent risk factors for predicting PFF were identified, namely age, female sex, hip revision, non-cemented prosthesis, history of trauma, and osteoporosis. The nomogram demonstrated sufficient predictive accuracy, with area under the curve (AUC) values of 0.798 (95% confidence interval [CI]: 0.725–0.872), 0.877 (0.798–0.957), and 0.804 (0.710–0.897) in the training, internal validation, and external validation cohorts, respectively. The calibration curve showed good consistency between the predicted risk of the model and the actual risk.

**Conclusions** The nomogram model for postoperative PFF after THA established in this study has good predictive value and helps identify high-risk populations.

**Keywords** Total hip arthroplasty, Periprosthetic fracture, Femur, Predictive modeling

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## Background

Total hip arthroplasty (THA) is an important surgical option for the treatment of severe osteoarthritis late-stage aseptic necrosis of the femoral head, rheumatoid arthritis, and femoral neck fractures among older patients [1, 2]. THA can effectively improve hip joint function, alleviate pain symptoms, and promote the recovery of independent living ability in patients [3, 4]. With the increasing number of THAs in recent years, postoperative periprosthetic femoral fracture (PFF) has become a key concern for surgeons [5].

The treatment of post-THA PFF is difficult, and patients with PFF who remain bed-bound for a long period have a higher risk of developing lower-limb venous thrombosis than those who regain activity. Moreover, the mortality rate of patients with fractures after hip replacement surgery was higher than that of patients without fractures [6, 7]. The previous study, which aimed to estimate the probability of death caused by fractures, has shown that at the age of 80 years, the estimated probability of death due to a fracture was 3.9% for men and 2.2% for women [8]. Therefore, identifying the risk factors for PFF after THA is of great significance, as it can guide clinical implementation of targeted protection, minimize the incidence of PFF, and ensure optimal postoperative rehabilitation for patients [9, 10].

There is currently a lack of effective, intuitive, and simple predictive models to guide patients undergoing THA in preventing postoperative PFF. The nomogram model is a reliable tool to quantify the risk of various diseases [11]. Therefore, we analyzed the influencing factors of postoperative periprosthetic fractures in THA patients and developed a nomogram prediction model aimed at forecasting the likelihood of such fractures occurring in these patients. This model is designed to predict whether periprosthetic fractures will occur in THA patients, thereby facilitating personalized fracture prevention strategies.

## Methods

### Study participants

Patients receiving THA treatment at Wuhan Fourth Hospital from January 2014 to August 2022 were included in the study. In addition, we also collected patient data from Renmin Hospital of Wuhan University from January 2018 to August 2022 as the external validation cohort.

Inclusion criteria: (1) All patients underwent THA; (2) no PFF before surgery; (3) complete clinical and imaging data; (4) minimum follow-up duration of 24 months.

Exclusion criteria: Patients with (1) undergoing THA for hip fracture; (2) hip joint tumors; (3) newly developed fractures during surgery; (4) postoperative prosthetic infection; (5) lost to follow-up.

### Surgical technique and implants

All patients underwent routine preoperative examinations. The condition of the hip joint was assessed based on anterior-posterior and lateral X-rays of the femur and hip joint. One day prior to surgery, all patients received antibiotics. Once their conditions were stable, they were positioned in a lateral decubitus position with the affected side up, and the surgery was performed under epidural anesthesia. The operation utilized an anterolateral approach to expose the joint capsule, which was then incised to reveal the femoral head and neck, identify the lesion site in the hip bone, and expose the fracture ends. The femoral head was removed, its length measured, and an appropriate artificial femoral head prosthesis was selected. The artificial femoral head was implanted at a 40° abduction angle and a 20° anteversion angle. Alternatively, a posterolateral surgical approach could also be used, following similar steps. Postoperatively, a drainage tube was placed in all patients, who subsequently received comprehensive treatments, including anti-infection therapy. Patients began walking exercises after suture removal and attended regular follow-up appointments. The THA surgeries were performed by four highly experienced senior surgeons at one institution. Bone or non-bone cement prosthesis were implanted by using the press-fit technique.

### Data collection

The electronic medical records were retrospectively reviewed for all patients and the following data were collected from identified patients: age, sex, body mass index (BMI), primary disease type, prosthesis coverage ratio, hip revision, prosthesis fixation method, history of hip infection, prosthesis type, trauma history (It refers to any past events involving physical injuries that an individual has experienced, including, but not limited to, traffic accidents, falls, and sports injuries), surgical approach, and osteoporosis status. The study was approved by the ethics committee of Wuhan Fourth Hospital (KY2024-175-01). All procedures performed in the study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee(s) and the Helsinki Declaration (as revised in 2013). The primary endpoint is the occurrence of PFF. Operations or procedures following the THA that were identified as PFF events matched the procedure codes for a THA revision, and featured a concurrent diagnosis of a femoral fracture.

### Statistical analysis

Data were input into Microsoft Excel and analyzed using SPSS version 22.0 (IBM Corporation, Armonk, NY, USA) and R 4.3.0 (The R Foundation for Statistical Computing, Vienna, Austria). Power was calculated based on the sample size using the pwr.p.test function in R. The normality of the distribution of continuous variables was evaluated according to the Shapiro–Wilk test with Q-Q plots. Non-normally distributed data were represented by median and interquartile range (IQR), and Kruskal–Wallis H test was used to examine the differences among the three cohorts. The count data were represented by [N (%)], and chi-square test was used for comparison. The Least Absolute Shrinkage and Selection Operator (LASSO) regression reduces the estimated parameters by incorporating a penalty term into the least squares method, thereby identifying prognostic factors that have a significant impact on the dependent variable [12]. Subsequently, based on the variables obtained from LASSO regression, a multivariate logistic regression analysis was conducted to investigate the risk factors for PFF and to construct a nomogram prediction model. Based on the predictive model, the performance of the nomogram model was evaluated in the training, internal validation, and external validation cohorts. The receiver operating characteristic (ROC) and calibration curves were used to evaluate the predictive performance of the model. The area under curve (AUC) of the ROC curve ranged from 0.50 to 1.00, and the closer the AUC to 1, the better the prediction performance. The concordance C-index (calculated using bootstrap resampling with 1000 iterations) and calibration curves (calculated using Hosmer-Lemeshow test) were used to evaluate the agreement between observed outcomes and predicted values [13]. To evaluate the clinical practicality of the model, decision curve analysis (DCA) was used to assess its effectiveness [14]. All statistical tests conducted were two-tailed, and $P < 0.05$ was considered to indicate statistical significance.

## Results

### General clinical characteristics

A total of 2,528 patients with THA were selected from Wuhan Fourth Hospital. They were randomly divided into two cohorts in a 7:3 ratio, with 1,770 patients assigned to the training cohort and 758 patients to the internal validation cohort. The external validation cohort comprised 1,383 routine THA patients from Wuhan University People's Hospital. The screening process is shown in Fig. 1, and the clinical characteristics of the patients are shown in Table 1. During the follow-up period, the incidence of PFF in the training, internal validation, and external validation cohorts was 2.03% (35/1770), 2.24% (17/758), and 1.81% (25/1383), respectively ($P = 0.779$).

### Predictive factors for PFF occurrence after THA

First, we preliminarily selected the predictive factors for PFF occurrence through LASSO regression. The variables were centralized and normalized through 10-fold cross validation (Fig. 2). The selected predictive factors were age, sex, hip revision, prosthesis type, history of trauma, and osteoporosis. Second, six predictive factors were included as independent risk variables, and a predictive model was constructed using multivariate logistic regression (Table 2). These six predictive factors were age (OR: 1.071, 95% CI: 1.033–1.109); sex (2.240, 1.032–4.862); hip revision (3.256, 1.589–6.672); prosthesis type (2.931, 1.306–6.576); history of trauma (2.358, 1.154–4.816); and osteoporosis (2.265, 1.139–4.507).

### Nomogram model of PFF occurrence after THA

A nomogram model was constructed to predict the risk of PFF after THA based on the above-mentioned six independent risk factors (Fig. 3). According to the nomogram, the sum of the score values corresponding to each predictive indicator was recorded as the total score. The predicted probability corresponding to the total score is the risk of developing PFF in THA patients.

### Calibration and validation of the nomogram model

Per the Hosmer–Lemeshow test, the chi-square values of the training, internal validation, and external validation cohorts were 9.057 ($P = 0.338$), 5.021 ($P = 755$), and 6.513 ($P = 0.590$), respectively. This result indicates that the predicted results are close to the observed results. The ROC curve in the training cohort showed good discrimination ability (AUC: 0.798; 95% CI: 0.725–0.872; sensitivity = 80.6%, specificity = 72.5%, positive predictive value (PPV) = 5.7%, negative predictive value (NPV) = 99.4%), and the C-index by bootstrap validation (1000 bootstrap samples) was 0.773, which embodied satisfying predictive performance. The discriminative performance of the model was validated in the internal validation cohort (0.877, 95% CI: 0.798–0.957; sensitivity = 76.5%, specificity = 87.9%, PPV = 12.6%, NPV = 99.4%) and the external validation cohort (0.804, 95% CI 0.710–0.897; sensitivity = 64.0%, specificity = 84.0%, PPV = 6.9%, NPV = 99.2%) (Fig. 4). In addition, calibration curve analysis showed that there was good consistency between the predicted probability and observed occurrence of PFF in both the training and validation cohorts (Fig. 5). DCA demonstrated the clinical practicality of the model (Fig. 6).

## Discussion

We have developed and validated a useful nomogram model for predicting PFF in high-risk patients undergoing THA. This new type of prediction tool has been successfully validated both internally and externally in different cohorts and has shown good discriminative power and calibration. This model includes six risk factors, namely age, sex, hip revision, prosthesis type, history of trauma, and osteoporosis.

Age was our primary consideration. Older patients are more likely to develop PFF after THA than younger

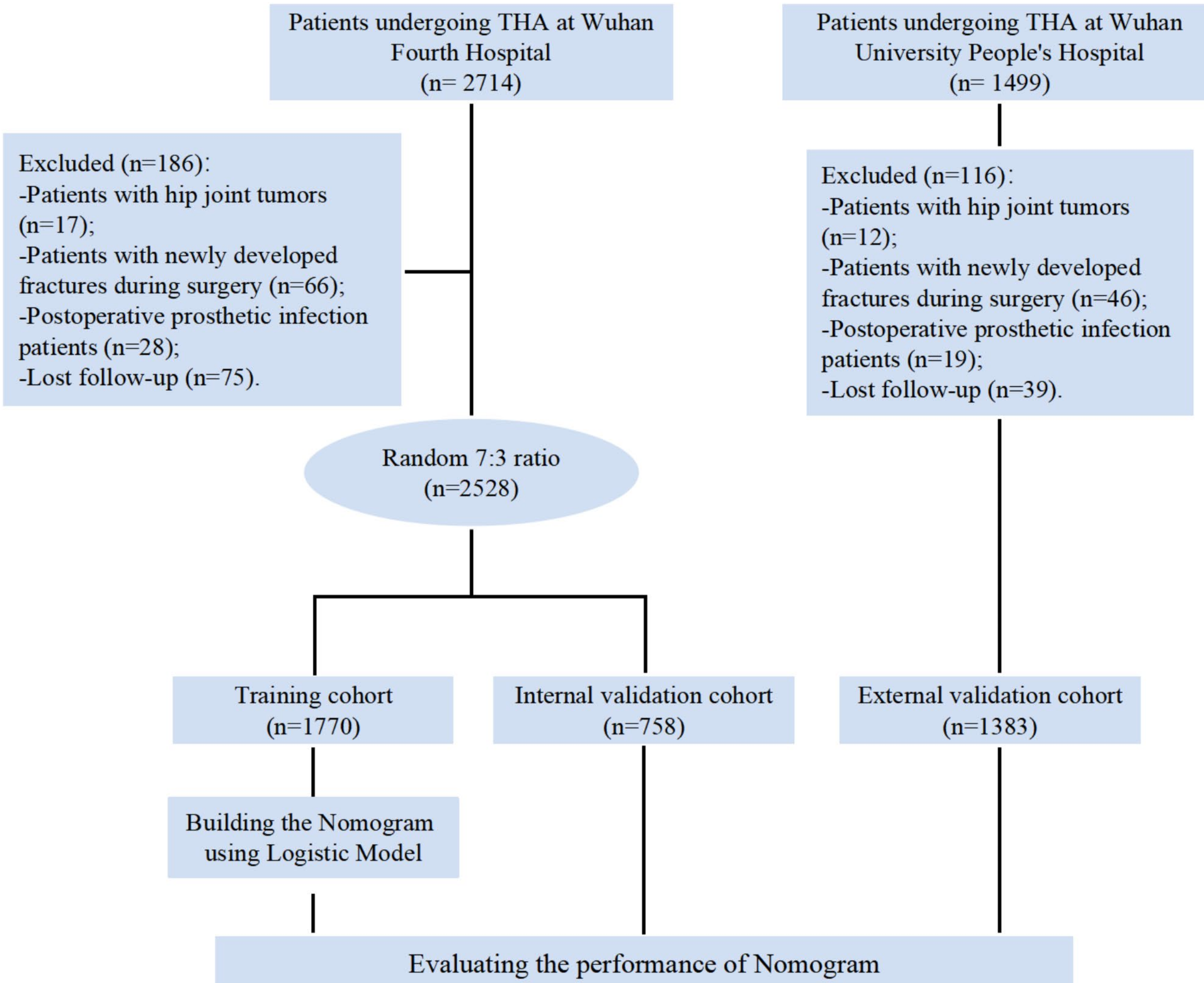


**Fig. 1** Patient screening process diagram

patients [6, 15]. Our research also shows that in the training cohort, the age of patients with PFF was significantly higher than that of patients without PFF. Older subjects often have osteoporosis or internal medicine diseases (cardiology or neurology), as well as mobility impairment and a tendency to fall, all of which increase the risk of PFF [6]. Ashkenazi et al. [16] also showed that advanced age is an important and independent risk factor for the occurrence of PFF. Meanwhile, a meta-analysis by Zhu et al. [17], which included seven studies, showed that advanced age (> 80 years) is an independent risk factor for developing PFF. However, some studies suggest that age does not pose a risk for the occurrence of PFF [18]. This is mainly due to the inclusion of sample size and the postoperative activity level of patients.

Patients with PFF patients are mostly women, and relevant literature reports show that female patients account for 66–84.1% of the total PFF cases. Therefore, many researchers believe that female sex is an important risk factor for PFF, which may be closely related to osteoporosis. After menopause, estrogen levels in women decrease, leading to increased bone resorption and decreased bone formation, further exacerbating osteoporosis [19, 20]. Baryeh et al. [21] found in a systematic review of 505 PFF patients that 61.2% were female.

Hip joint revision has been proven to be one of the important risk factors for PFF [22, 23], mainly because of the multiple surgeries causing damage to the tissue structure around the hip joint, weakening its stability and strength [23]. Deng et al. [20] also showed that the incidence of PFF caused by hip revision is three times higher than that of first-time THA patients. Zhang et al. [24] reported that hip revision significantly increases the risk of PFF owing to local tissue damage and structural changes caused by multiple surgeries. At the same time, loosening, displacement, hip bone defects, and reduced bone mass are the main reasons for hip joint revision. Moreover, during hip joint revision, procedures such as

**Table 1** Population statistics of the THA patients

| Item | Training cohort ($n$ = 1770) | Internal verification cohort ($n$ = 758) | Extremal verification cohort ($n$ = 1383) | $H/\chi^2$ | *P*-value |
|---|---|---|---|---|---|
| Age (years), M(P25/P75) | 70 (62–75) | 72 (62–78) | 71 (64–77) | 2.657 | 0.265 |
| Female (yes), n (%) | 1024 (57.9) | 447 (59.0) | 811 (58.6) | 0.348 | 0.840 |
| BMI (kg/m$^2$), M(P25/P75) | 23.2 (21.4–24.4) | 23.1 (21.5–25.1) | 22.8 (20.9–24.4) | 0.826 | 0.662 |
| Primary disease type, n (%) | | | | 15.431 | 0.051 |
| Femoral head necrosis | 598 (33.8) | 243 (32.1) | 407 (29.4) | | |
| Femoral neck fracture | 659 (37.2) | 275 (36.3) | 540 (39.0) | | |
| Dysplasia of hip joint | 268 (15.1) | 106 (14.0) | 201 (14.5) | | |
| Rheumatoid arthritis | 142 (8.0) | 87 (11.5) | 141 (10.2) | | |
| Osteoarthritis | 103 (5.8) | 47 (6.2) | 94 (6.8) | | |
| Coverage ratio of prosthesis, n (%) | | | | 3.032 | 0.220 |
| ≤ 80% | 320 (18.1) | 124 (16.4) | 268 (19.4) | | |
| >80% | 1450 (81.9) | 634 (83.6) | 1115 (80.6) | | |
| Hip joint revision (yes), n (%) | 307 (17.3) | 148 (19.5) | 223 (16.1) | 3.952 | 0.139 |
| Fixed prosthesis material, n (%) | | | | 7.342 | 0.025 |
| Bone cement | 1026 (58.0) | 434 (57.3) | 737 (53.3) | | |
| Non–bone cement | 744 (42.0) | 324 (42.7) | 646 (46.7) | | |
| Type of prosthesis, n (%) | | | | 9.272 | 0.010 |
| Bone cement | 765 (43.2) | 374 (49.3) | 649 (46.9) | | |
| Non–bone cement | 1005 (56.8) | 384 (50.7) | 734 (53.1) | | |
| History of trauma (yes), n (%) | 818 (46.2) | 367 (48.4) | 593 (42.9) | 6.799 | 0.033 |
| Surgical approach, n (%) | | | | 0.218 | 0.897 |
| Front outer side | 400 (22.6) | 175 (23.1) | 322 (23.3) | | |
| Rear outer side | 1370 (77.4) | 583 (76.9) | 1061 (76.7) | | |
| Osteoporosis (yes), n (%) | 688 (38.9) | 292 (38.5) | 483 (34.9) | 5.662 | 0.059 |
| PFF (yes), n (%) | 36 (2.03) | 17 (2.24) | 25 (1.81) | 0.500 | 0.779 |

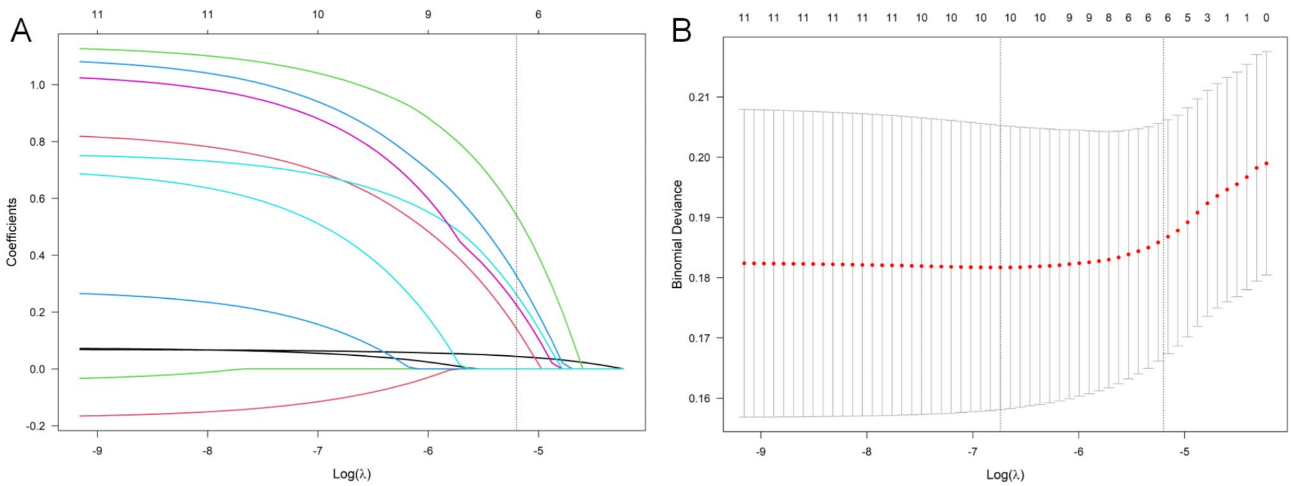


**Fig. 2** LASSO coefficient curve of PFF after THA. A: Each curve in the graph represents the coefficient variation of each variable. The vertical axis represents the coefficient values, the lower horizontal axis represents log (λ), and the upper horizontal axis represents the number of non-zero coefficients in the model at this time. B: The model was selected after 10-fold cross validation fitting

**Table 2** Multivariate logistic regression analysis of predictive factors selected through LASSO regression program for development concentration

| Independent variables | B | 95% CI | *P* |
|---|---|---|---|
| Age | 0.068 | 1.071 (1.033–1.109) | 0.001 |
| Female sex | 0.806 | 2.240 (1.032–4.862) | 0.01 |
| Hip revision | 1.181 | 3.256 (1.589–6.672) | 0.001 |
| Non-cemented prosthesis | 1.075 | 2.931 (1.306–6.576) | 0.023 |
| History of trauma | 0.858 | 2.358 (1.154–4.816) | 0.022 |
| Osteoporosis | 0.818 | 2.265 (1.139–4.507) | 0.008 |

Note: B is the regression coefficient, CI: confidence interval

removal and re-implantation of the prosthesis may cause PFF [24]. For patients who have undergone hip joint revision, doctors should be more vigilant about the occurrence of postoperative PFF and strengthen postoperative monitoring and care.

The results of this study indicate that non-cemented prostheses are also one of the important risk factors for PFF after THA. This is mainly because compared to cemented implants, non-cemented implants have certain shortcomings in terms of binding and stability with bone tissue, thereby increasing the risk of PFF [25]. Konow et al. [26] also pointed out that in patients undergoing hip replacement surgery, the incidence of PFF is significantly higher in non-cemented prostheses than in cemented prostheses. This is because non-cemented prostheses need to have a good compression fit with the femur and prosthesis to achieve stable results. However, in actual operation, the femur usually experiences greater pressure, which can cause the bent portion of the prosthesis to be completely mismatched with the femur, thereby increasing the risk of PFF [25, 26]. Therefore, in clinical practice, doctors need to comprehensively consider the individual situation of patients when choosing the type of prosthesis and weigh the advantages and disadvantages of different prosthesis types to reduce the risk of postoperative complications.

History of trauma is a common risk factor and has been confirmed to be closely related to PFF in this study. This is consistent with the study results by Zhang et al. [27]. External trauma can alter the bone structure of patients undergoing hip replacement surgery, have varying degrees of impact on biomechanical properties, and thus increase the probability of PFF [28]. Therefore, doctors should pay more attention to the postoperative follow-up of patients with a history of trauma.

The results of this study suggest that osteoporosis is a risk factor for developing PFF. Osteoporosis is also recognized by scholars as a risk factor for PFF [29, 30]. This is mainly because osteoporosis can affect bone metabolism and alter its biomechanical properties, leading to increased bone fragility and decreased bone strength. Therefore, when subjected to external forces, THA patients are prone to PFF. Layson et al. [31] found that osteoporosis can lead to a decrease in bone density and strength, making it difficult for the bones around the hip joint to withstand the pressure and impact of implants. Therefore, for patients with osteoporosis, active anti-osteoporosis treatment should be offered before and

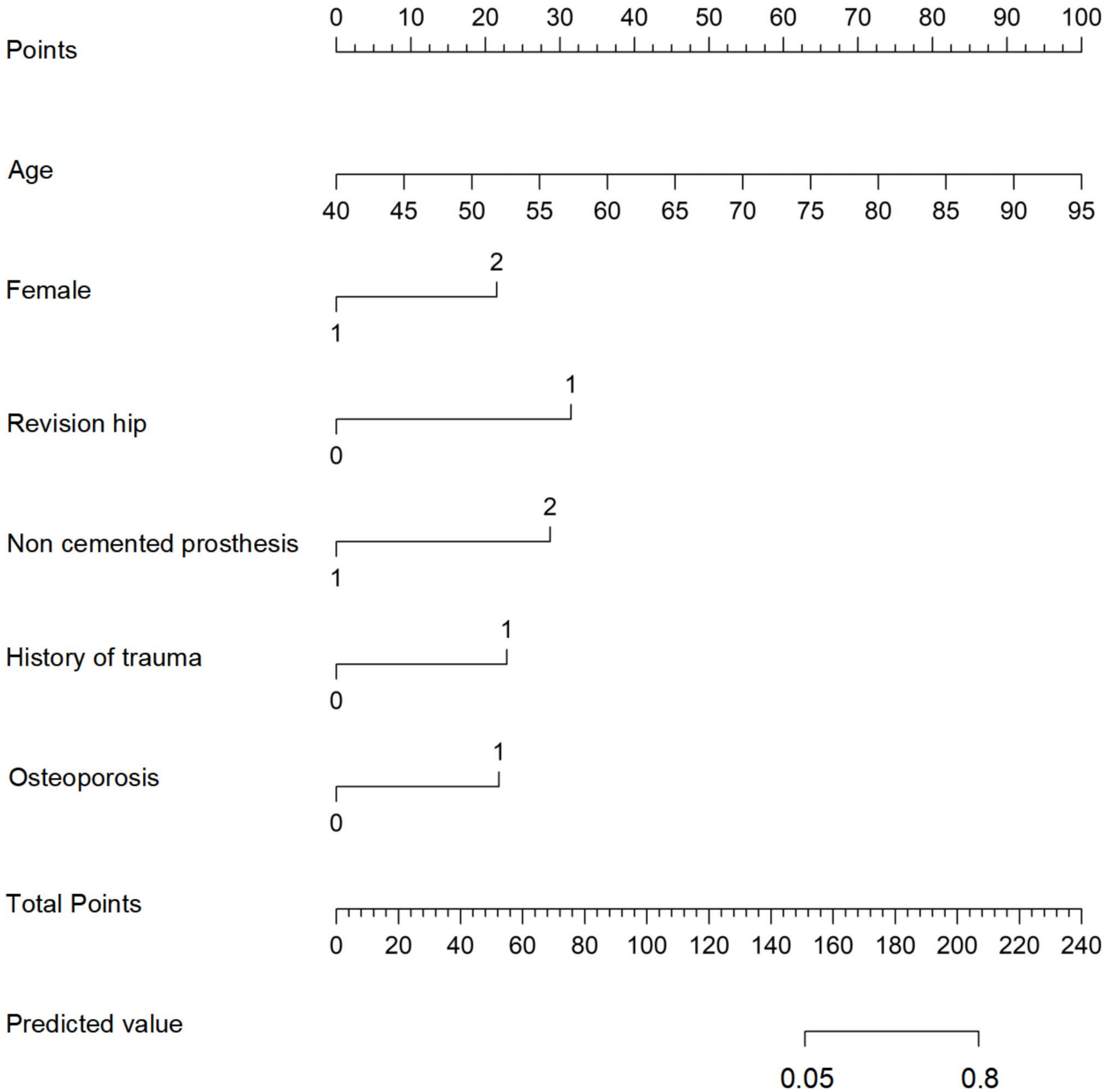


**Fig. 3** Nomogram of PFF occurrence after THA. Each level of the predictor variable represents a specific score. The total score is generated by summarizing the scores of each predictor variable. The total score corresponds to the probability of PEF

after THA to improve bone quality and reduce the risk of fractures.

The application of the nomogram model in the medical field has become increasingly widespread, which can help doctors better diagnose and treat diseases. First, this study synthesized six independent risk factors and constructed a nomogram model to predict PFF after THA. These six factors are clinically easy to measure and routinely available, and these predictive factors were established in a well-characterized training cohort of patients undergoing THA. Second, our model has been successfully validated in two independent cohorts, thereby improving its universality and credibility. In clinical practice, both orthopedic surgeons and patients can benefit from this easy-to-use model to assess the risk of developing PFF post-THA. Orthopedic surgeons can have a more intuitive understanding of the risks that patients may face, so that they can intervene in advance with risk factors and formulate more individualized and precise treatment strategies for the patients. Meanwhile, we believe that the nomogram model could help patients set realistic expectations after THA, potentially

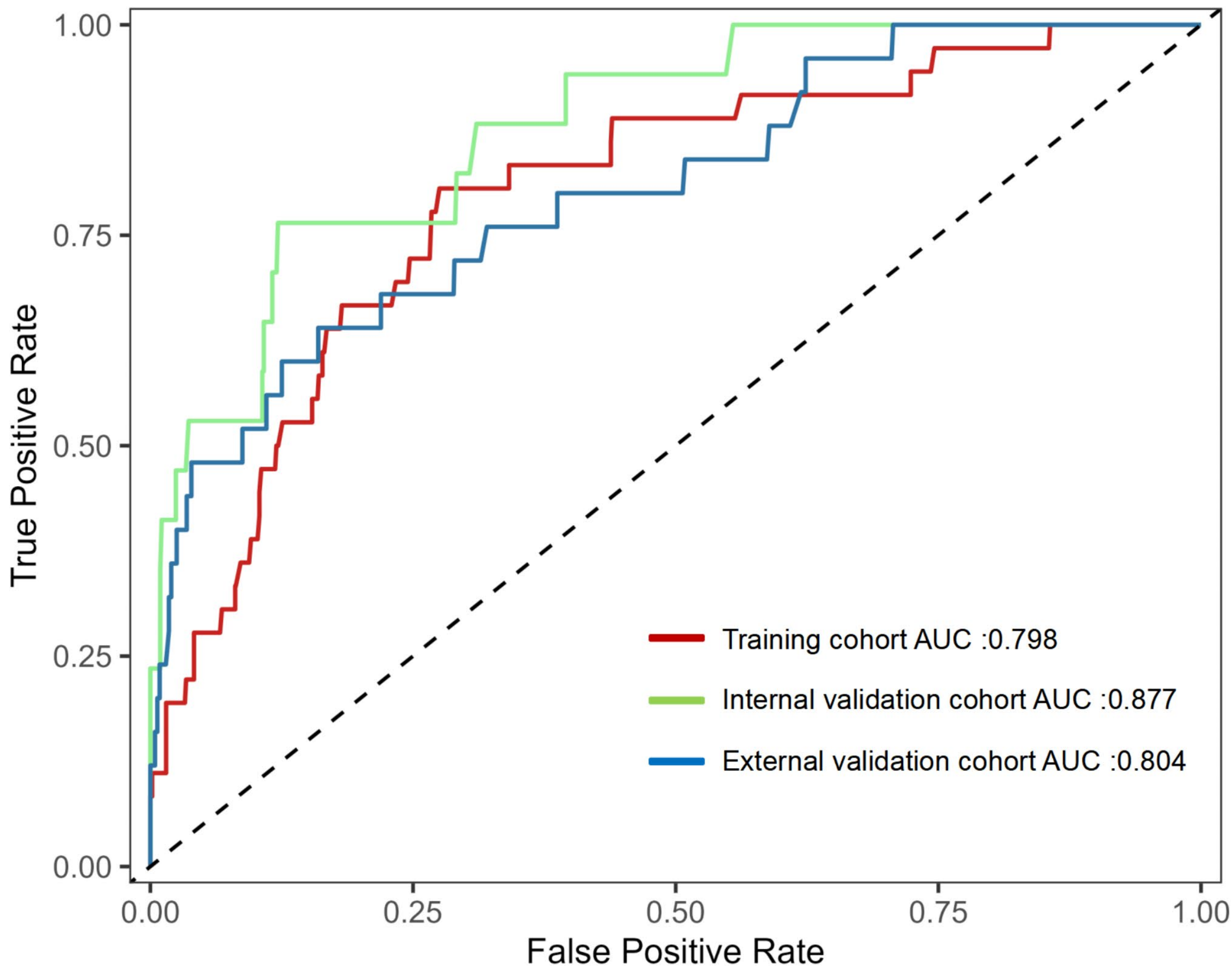


**Fig. 4** ROC curve and AUC of the prediction model. ROC: receiver operating characteristic; AUC: area under the curve

enhancing patient compliance. At present, there is still a lack of effective evaluation criteria for the treatment of PFF, making it difficult to compare the treatment outcomes of PFF with other treatments such as revision of aseptic loosening. Therefore, patients at high risk of PFF should be closely followed-up to reduce the risk factors of PFF and seek lifestyle guidance.

This study has some limitations. First, our research design is essentially retrospective, which involves potential selection bias and limits our ability to establish causal relationships. Second, neither group was randomly assigned, and baseline information may be imbalanced and biased. Third, because of the retrospective design, we had to rely on medical records and hence, it is possible that some relevant information or factors that affect patient outcomes may have been missed. For example, comorbid diseases and radiological measures. Fourth, the risk factors included in this study may not be comprehensive, and other potential factors such as patients' nutritional status, comorbidities, and rehabilitation training may also have an impact on the occurrence of postoperative PFF. Finally, the repeatability and robustness of nomograms need to be validated in prospective multicenter studies with larger datasets.

## Conclusion

Age, female sex, hip revision, non-cemented prosthesis, history of trauma, and osteoporosis are all important risk factors for PFF after THA. The nomogram prediction model constructed based on this showed good discrimination ability and clinical utility, which would be a reliable and convenient tool to assist orthopedic surgeons in identifying high-risk patients and formulate individualized treatment strategies.

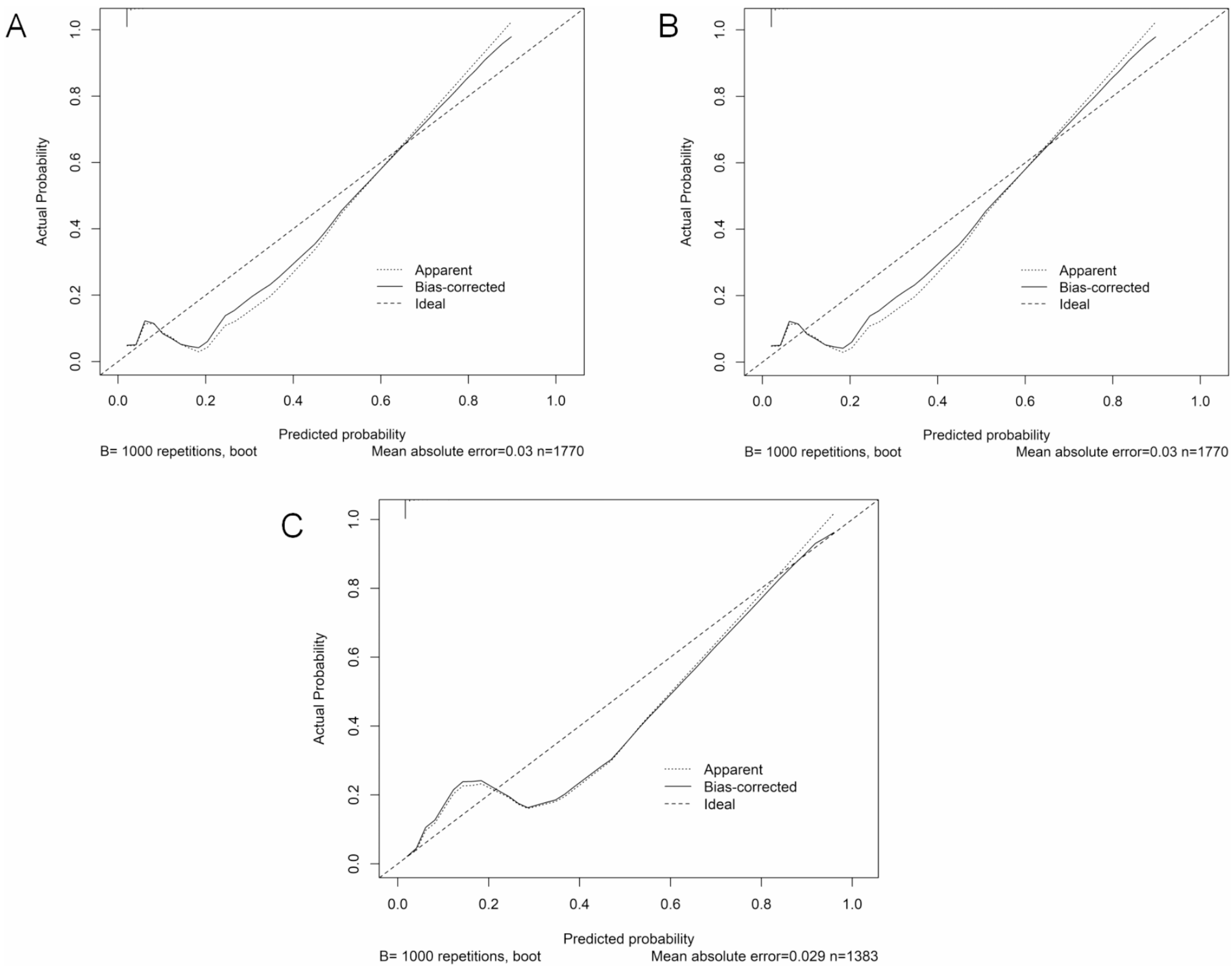


**Fig. 5** Calibration diagram of the prediction model. **A**: Calibration chart of the training cohort. **B**: Calibration chart of the internal validation cohort. **C**: Calibration chart of the external validation cohort. The X-axis represents the predicted probability of PFF. The Y-axis represents the observed PFF. The diagonal dashed line represents the perfect prediction of the ideal model. The solid line represents the performance of the nomogram. It indicates that solid lines are closer to diagonal dashed lines for better prediction. This figure shows that the prediction model has good predictive ability

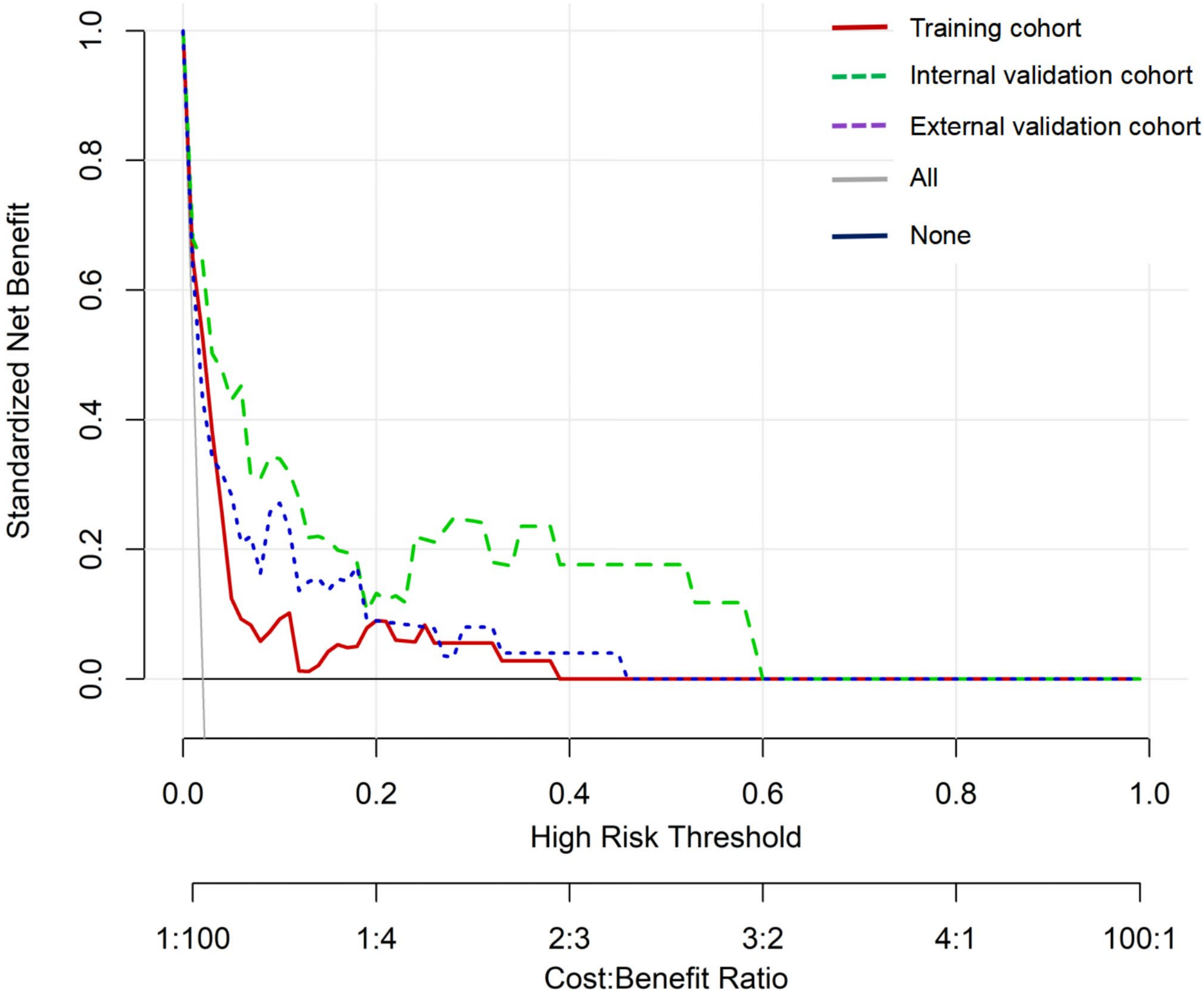


**Fig. 6** DCA of the nomogram. DCA: decision curve analysis

**Abbreviations**

| | |
|---|---|
| AUC | Area under the curve |
| BMI | Body mass index |
| DCA | Decision curve analysis |
| LASSO | Least Absolute Shrinkage and Selection Operator |
| NPV | Negative predictive value |
| PPV | Positive predictive value |
| PFF | Periprosthetic femoral fracture |
| ROC | Receiver operating characteristic |
| THA | Total hip arthroplasty |

**Acknowledgements**
None.

**Author contributions**
JT and YH conceptualized and drafted the manuscript; JT, YH and YL conducted data collection and processing; SZ and YH performed data analysis and engaged in constructive discussions. All authors contributed to the writing and editing of this article and have reviewed and approved the final version for submission.

**Funding**
This study did not involve any related funding.

**Data availability**
Our study only collected the clinical data of patients and did not interfere with the treatment plan of patients. The datasets related to this study are not publicly available due to privacy or ethical restrictions but are available from the corresponding author on reasonable request.

## Declarations

**Ethics approval and consent to participate**
All procedures performed in the study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee(s) and the Helsinki Declaration (as revised in 2013). The requirement for informed consent was waived by the ethics committee due to the observational and retrospective nature of the study. This study was approved by the ethics committee of Wuhan Fourth Hospital (KY2024-175-01).

**Consent for publication**
Not applicable.

**Competing interests**
The authors declare no competing interests.

Received: 26 September 2024 / Accepted: 24 March 2025

Published online: 05 April 2025

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