Risk Factors for Failure of Internal Fixation in Postmenopausal Patients With Osteoporotic Intertrochanteric Fractures

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AIM: To identify independent risk factors for internal fixation failure after intramedullary nail fixation in postmenopausal patients with osteoporotic intertrochanteric fractures, and to develop and internally validate a predictive model for risk assessment.
METHODS: The clinical data of 360 postmenopausal patients with osteoporotic intertrochanteric fractures admitted to The Second Affiliated Hospital of Liaoning University of Traditional Chinese Medicine from January 2021 to May 2024 were retrospectively analyzed. The patients were divided into the failure group (n = 65) and the success group (n = 295) according to whether internal fixation failure occurred within 6 months after the operation. General data, bone metabolism indices, imaging parameters, and surgery-related factors were collected. Univariate and multivariate logistic regression analyses were used to screen the independent risk factors of internal fixation failure. The receiver operating characteristic (ROC) curve was used to evaluate the model's discriminative ability, while the Hosmer–Lemeshow test and bootstrap resampling calibration curve were used to evaluate calibration. Decision curve analysis was used to assess the clinical utility of the model.
RESULTS: The failure rate of internal fixation was 18.06% (65/360). Multivariate logistic regression analysis showed that the quality of fracture reduction was poor (odds ratio (OR) = 3.07, 95% CI: 1.60–5.87, $p < 0.01$). The intramedullary nail position deviated from the center of the medullary cavity (OR = 2.38, 95% CI: 1.13–5.01, $p = 0.02$) was identified as an independent risk factor for internal fixation failure, whereas bone mineral density (BMD) T-score (OR = 0.17, 95% CI: 0.06–0.47, $p < 0.01$), femoral cortical thickness index (OR = 0.54, 95% CI: 0.38–0.79, $p < 0.01$), and lateral wall thickness (OR = 0.83, 95% CI: 0.76–0.90, $p < 0.01$) were independent protective factors. The model demonstrated good performance, with an area under the curve (AUC) of 0.83 (95% CI: 0.77–0.89). The Hosmer–Lemeshow test showed no significant difference between the predicted probability of the model and the actual observation ($p = 0.28$), and the calibration curve closely aligned with the ideal line. Decision curve analysis showed that the model had significant net clinical benefit within a wide threshold probability range.
CONCLUSIONS: Poor quality of fracture reduction, the position of the intramedullary nail deviated from the center of the medullary cavity, lower bone mineral density, lower femoral cortical thickness index, and smaller lateral wall thickness are independent risk factors for the failure of internal fixation after intramedullary nail fixation in postmenopausal women with osteoporotic intertrochanteric fractures. The predictive model based on these factors demonstrates good discrimination, calibration, and clinical utility. Clinicians should pay close attention to the identified risk factors, thoroughly evaluate preoperative bone quality, achieve anatomical reduction, and ensure optimal positioning of the main nail during operation to reduce the risk of internal fixation failure and improve patient outcomes.

Keywords: postmenopausal osteoporosis; intertrochanteric fracture; intramedullary nail; internal fixation failure

Introduction

Femoral intertrochanteric fracture is one of the most common types of hip fractures in the elderly. Its incidence is increasing on an annual basis with the rapid aging of the population. Epidemiological surveys show that hip fractures account for approximately 20% of all fractures, among which the ratio of intertrochanteric fractures to femoral neck fractures is about 1.5:1 [1]. Due to the significant decrease in estrogen levels, enhanced osteoclast activity, accelerated bone loss, bone microstructure destruction, and more severe osteoporosis in postmenopausal women than men of the same age [2], postmenopausal women constitute the highest-risk group of femoral intertrochanteric fracture. Femoral intertrochanteric fracture often leads to a series of complications, such as long-term bed rest, deep vein thrombosis, pulmonary infection, and pressure sores, sig-

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nificantly lowering patients' quality of life and imposing a heavy strain on their family and the medical resources [3].

At present, surgery remains the principal mode of treatment for femoral intertrochanteric fractures [4], with a primary function of restoring walking function and mitigating complications caused by long-term bed rest. Intramedullary nail internal fixation systems, such as proximal femoral nail antirotation (PFNA) and InterTan, have become the mainstream surgical methods for the treatment of intertrochanteric fractures due to their biomechanical advantages, such as a closer force line to the center of the femoral head, shorter moment arm, and smaller bending moment [5,6,7]. Compared with the traditional dynamic hip screw, the intramedullary nail can better protect the lateral wall of the femur, especially for patients with unstable fractures and osteoporosis [5,8]. Although increasingly refined surgical techniques are available to manage this medical issue and increasingly improved internal fixation materials are being developed, internal fixation failure remains a serious clinical complication that cannot be neglected. The incidence of internal fixation failure after intramedullary nail internal fixation is about 5%–20%, mainly characterized by helical blade cutting, cutting out, coxa vara deformity, screw withdrawal, internal fixation fracture, or fracture nonunion [9,10,11]. The occurrence of internal fixation failure often necessitates a second revision surgery or even artificial hip replacement, which not only exacerbates the pain and financial burden but also makes the treatment more complex and intractable.

Therefore, in-depth exploration of the risk factors of internal fixation failure after intramedullary nail fixation in postmenopausal patients with osteoporotic intertrochanteric fractures is of great clinical significance for early postoperative risk assessment, intraoperative precise operation, and postoperative individualized management. Some previous studies have investigated the risk factors for the failure of internal fixation of intertrochanteric fractures, but they generally suffer from several limitations, namely utilization of non-stratified samples as subjects, small sample size, and univariate analysis. In studies that specifically targeted postmenopausal osteoporosis, the samples were relatively limited. Postmenopausal women with osteoporosis typically exhibit poor bone quality, characterized by cortical bone thinning, trabecular bone loss, and significantly reduced fixation strength between the internal implants and the bone. As a result, the risk factors for internal fixation failure in these patients may differ from those observed in patients without osteoporosis.

The present study retrospectively analyzed the clinical data of 360 postmenopausal patients with osteoporotic intertrochanteric fractures treated in The Second Affiliated Hospital of Liaoning University of Traditional Chinese Medicine. Through univariate and multivariate logistic regression analysis, we systematically evaluated the influence of multiple potential factors on internal fixation failure, such as age, body mass index, bone mineral density, femoral cortical thickness index, lateral wall thickness, fracture reduction quality, and the intramedullary nail position, to identify independent risk factors. At the same time, receiver operating characteristic (ROC) curve analysis was performed to evaluate the model's discriminative ability. Decision curve analysis was used to evaluate the clinical utility of the model, providing more reliable evidence to guide early postoperative risk assessment in clinical settings. The primary goal of this work is to improve the prognosis of postmenopausal patients with osteoporotic intertrochanteric fractures.

Methods

Subjects

A total of 360 patients with postmenopausal osteoporotic intertrochanteric fractures admitted to The Second Affiliated Hospital of Liaoning University of Traditional Chinese Medicine from January 2021 to May 2024 were enrolled. This study was conducted in strict accordance with the principles of the Declaration of Helsinki and was approved by the Ethics Committee of The Second Affiliated Hospital of Liaoning University of Traditional Chinese Medicine (2024(XS)-011-02(FS)). Inclusion criteria of this study include: (1) patients with osteoporosis (diagnosed using dual-energy X-ray absorptiometry [DXA] at the femoral neck, with a T-score ≤ -2.5 according to the World Health Organization [WHO] diagnostic criteria for osteoporosis [12]); (2) postmenopausal women; (3) patients with fresh unilateral intertrochanteric fracture; (4) patients who had received domestic Proximal Femoral Nail Antirotation (PFNA) internal fixation; and (5) patients with complete clinical and imaging data. Exclusion criteria of this study are as follows: (1) pathological fractures or concomitant fractures at other sites; (2) severe cardiac, pulmonary, hepatic, or renal dysfunction that precluded surgery; and (3) a history of ipsilateral hip surgery. Among the 390 postmenopausal patients initially assessed for eligibility during the study period, 13 were excluded for pathological or concomitant fractures, 8 for severe organ dysfunction, 5 for prior ipsilateral hip surgery, and 4 for incomplete clinical or imaging data. The remaining 360 patients met all inclusion criteria and were included in the analysis. All 360 patients completed the 6-month follow-up, with no loss to follow-up. The patients were followed up for 6 months postoperatively. Internal fixation failure was defined as the occurrence of any of the following during postoperative follow-up: internal fixation loosening, fracture displacement, helical blade cutting, or screw withdrawal. According to the occurrence of internal fixation failure, patients were divided into a failure group ($n = 65$) and a success group ($n = 295$).

Data Collection

The following data of patients were collected: (1) general data, including age, body mass index (BMI), residence (urban/rural), and injury mechanism (high energy/low energy); (2) history of hypertension, diabetes, and rheumatic

diseases; (3) perioperative indicators such as intraoperative blood loss and operative time; (4) bone metabolism indicators, including menopausal time and bone mineral density (BMD) T-score; (5) imaging indicators such as femoral cortical thickness index, lateral wall thickness, fracture type (31A1/31A2/31A3), fracture side (left/right), posteromedial wall integrity (complete/incomplete); (6) surgery-related factors, including intramedullary nail position (centrally positioned/eccentrically positioned) and quality of fracture reduction (good/poor).

Relevant Definitions and Measurement Methods

Injury mechanisms were classified as low-energy or high-energy trauma based on the documented circumstances of injury. Low-energy trauma primarily included falls from standing height or less, whereas high-energy trauma included traffic accidents, falls from a height, and other high-impact injuries. All postoperative radiographs were independently evaluated by two senior orthopedic residents who were blinded to the patients' clinical information and group allocation (failure vs. success). In case of disagreement, a consensus was reached by consultation with a third attending orthopedic surgeon. The standardized radiographic criteria for each failure subtype were defined as follows: helical blade cut-out/cutting was defined as penetration of the blade through the femoral head cortex; screw withdrawal was defined as outward migration of the screw >5 mm from its initial position; fracture end displacement was defined as varus collapse or fracture gap >5 mm; and internal fixation loosening was defined as the presence of radiolucent lines around the screw or breakage of the main nail. These definitions were derived from previous studies [10,11,13,14]. The parameters or indices used in this study were measured (or defined) as follows: (i) femoral cortical thickness index: The ratio of the sum of the medial and lateral femoral cortical thickness at 2 cm below the lesser trochanter to the femoral diameter at this plane was measured on preoperative standard anteroposterior radiographs. (ii) Lateral wall thickness: The cortical thickness (mm) of the thinnest lateral wall of the proximal femur was measured on anteroposterior radiographs during or immediately after surgery. (iii) Intramedullary nail position: Intramedullary nail position was assessed on immediate postoperative anteroposterior radiographs. A nail tip located in the center of the femoral medullary cavity was defined as "centrally positioned". Deviation of the nail tip toward the medial or lateral cortical wall was defined as "eccentrically positioned (medial or lateral)" (iv) Fracture reduction quality: good quality refers to fracture alignment >90% on anteroposterior and lateral films, with normal or nearly normal neck-shaft angle and no varus deformity, whereas poor quality refers to fracture alignment ≤90% or presence of obvious varus, rotation, or separation displacement.

Statistical Methods

SPSS 26.0 (IBM Corp., Armonk, NY, USA) or R 4.2 (R Foundation for Statistical Computing, Vienna, Austria) software was used for statistical analysis. The normality of continuous variables was assessed using the Shapiro–Wilk test. Continuous variables with normal distribution were expressed as mean ± standard deviation (SD), and an independent sample *t*-test was used for comparison between the two groups. Continuous variables that do not conform to normal distribution were expressed as median (interquartile range) [M (Q_1, Q_3)], and the Mann–Whitney *U* test was used for comparison between the two groups. Categorical variables were expressed as count and percentage [n (%)], and the chi-square test was used for comparison between groups. Before constructing the multivariate logistic regression model, the linearity assumption between continuous predictors and the logit function was assessed. To robustly determine the appropriate functional form and test for non-linearity, fractional polynomial (FP) analysis was performed using the mfp package in R. Continuous variables were allowed to fit first-degree (FP1) or second-degree (FP2) fractional polynomials. The final selection between linear and non-linear models was based on the likelihood ratio test. Candidate variables selected *a priori* based on clinical knowledge and relevant literature were entered into univariate logistic regression analysis, and variables with $p < 0.05$ in univariate analysis were included in the multivariate logistic regression model via stepwise backward method to determine the independent risk factors. Given the limited number of events ($n = 65$), we adhered to the commonly recommended rule of including no more than 10–15 candidate variables per event to avoid overfitting. The events-per-variable (EPV) ratio for the final multivariate model was 13.0 (65 events / 5 variables), which exceeds the commonly recommended minimum of 10, indicating that the model was not overfitted and the regression estimates were reliable. The results were expressed as odds ratios (ORs) and 95% confidence intervals (CIs). The discriminative ability of the model was evaluated by the ROC curve and the area under the curve (AUC). The model calibration was evaluated using the Hosmer–Lemeshow goodness-of-fit test and calibration curve. To account for overfitting, we performed internal validation using bootstrap resampling with 1000 resamples to calculate optimism-corrected AUC, calibration slope, intercept, and Brier score. Clinical utility was evaluated by means of decision curve analysis (DCA). The statistical significance threshold set for this study was $\alpha = 0.05$ (two-sided).

Results

Baseline Data of Patients

A total of 360 patients with postmenopausal osteoporotic intertrochanteric fractures were enrolled, including 65 cases (18.06%) in the failure group and 295 cases (81.94%) in the success group. Among the 65 patients in the failure group,

the distribution of failure subtypes was as follows: helical blade cutting/cut-out in 28 cases (43.1%), screw withdrawal in 15 cases (23.1%), fracture end displacement in 12 cases (18.5%), and internal fixation loosening in 10 cases (15.4%). Each patient was classified into only one failure subtype, and no overlap between failure subtypes occurred. The 6-month follow-up period was chosen because the vast majority of mechanical failures occur within this timeframe. There were no significant differences in age, BMI, intraoperative blood loss, operative time, menopause time, residence, injury mechanism, complications (hypertension, diabetes, rheumatic diseases), fracture side, fracture type, and posteromedial wall integrity between the two groups ($p > 0.05$). Compared with the success group, the failure group had significantly lower femoral cortical thickness index (0.39 ± 0.08 vs. 0.45 ± 0.09, $p < 0.01$), BMD T-score (−3.23 vs. −3.01, $p < 0.01$), and lateral wall thickness (22.20 mm vs. 24.90 mm, $p < 0.01$). In addition, the proportion of eccentric intramedullary nail position (33.85% vs. 11.86%, $p < 0.01$) and poor fracture reduction quality (60.00% vs. 31.19%, $p < 0.01$) in the failure group was significantly higher than that in the success group. Table 1 presents the overall baseline data of the patients in both success and failure groups.

Univariate and Multivariate Logistic Regression Analysis

The linearity assumption for the continuous predictors was evaluated using fractional polynomial analysis. The results demonstrated that a linear term (first-degree polynomial, power = 1) was the best fit for all continuous variables (all p values for non-linearity >0.05). Therefore, all continuous variables were retained as linear terms in the final multivariate model. Multicollinearity assessment using the variance inflation factor (VIF) showed that all continuous predictors had VIF values below 1.1 (BMD T-score: VIF = 1.050; femoral cortical thickness index: VIF = 1.047; lateral wall thickness: VIF = 1.006), indicating no significant multicollinearity among the bone quality-related variables. Univariate logistic regression analysis showed that the eccentric intramedullary nail position (OR = 3.80, 95% CI: 2.04–7.09, $p < 0.01$) and the poor fracture reduction quality (OR = 3.31, 95% CI: 1.90–5.76, $p < 0.01$) were significantly associated with an increased risk of internal fixation failure. In contrast, a higher BMD T-score (OR = 0.12, 95% CI: 0.05–0.29, $p < 0.01$), greater femoral cortical thickness index (OR = 0.50, 95% CI: 0.36–0.69, $p < 0.01$), and greater lateral wall thickness (OR = 0.84, 95% CI: 0.78–0.90, $p < 0.01$) were significantly associated with a reduced risk of internal fixation failure (Table 2).

The identified statistically significant factors were further included in multivariate logistic regression analysis, and the results showed that eccentric intramedullary nail position (OR = 2.38, 95% CI: 1.13–5.01, $p = 0.02$) and poor fracture reduction quality (OR = 3.07, 95% CI: 1.60–5.87, $p < 0.01$) were independent risk factors for internal fixation failure in postmenopausal patients with osteoporotic intertrochanteric fractures. In contrast, BMD T-score (OR = 0.17, 95% CI: 0.06–0.47, $p < 0.01$), femoral cortical thickness index (OR = 0.54, 95% CI: 0.38–0.79, $p < 0.01$), and lateral wall thickness (OR = 0.83, 95% CI: 0.76–0.90, $p < 0.01$) were independent protective factors (Table 3). Based on the multivariate logistic regression analysis, the complete regression equation for calculating the predicted probability (P) of internal fixation failure is as follows: Logit(P) = –0.84 + (0.87 × Nail Position) + (1.12 × Reduction Quality) – (1.77 × BMD T-score) – (0.61 × Femoral Cortical Thickness Index) – (0.19 × Lateral Wall Thickness), where P = 1 / (1 + e^(–Logit(P))). Categorical predictors were coded as follows: Intramedullary nail position (1 = centrally positioned, 2 = eccentrically positioned); Fracture reduction quality (1 = good, 2 = poor). Continuous variables (BMD T-score, femoral cortical thickness index, and lateral wall thickness) were entered as their actual measured values.

Evaluation of the Model's Predictive Performance

The AUC of the predictive model based on multivariate logistic regression was 0.83 (95% CI: 0.77–0.89) (Fig. 1). After bootstrap internal validation (1000 resamples), the optimism-corrected AUC was 0.82 (95% CI: 0.77–0.88), indicating good discriminative performance with only minimal overfitting. The Brier score of the model was 0.12, suggesting satisfactory overall predictive accuracy.

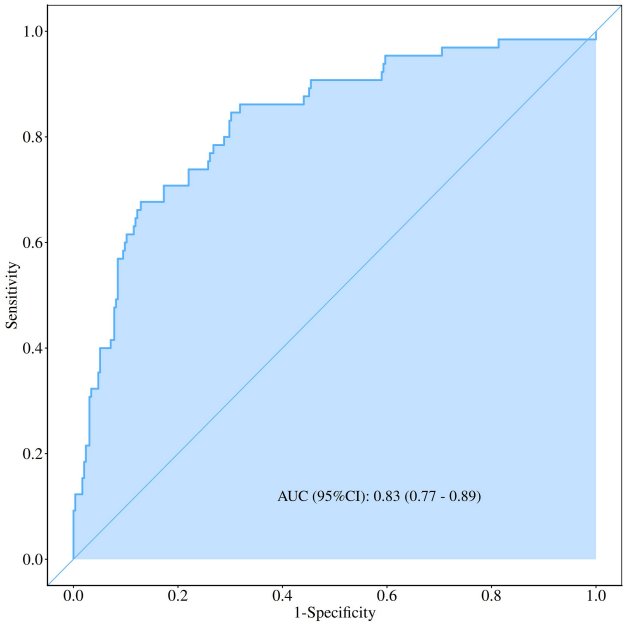


Fig. 1. ROC curve for predicting the risk of internal fixation failure. Abbreviations: AUC, area under the curve; ROC, receiver operating characteristic.

Model Calibration and Clinical Utility Evaluation

The Hosmer–Lemeshow goodness of fit test ($\chi^2 = 9.78$, df = 8, $p = 0.28$) showed no significant difference between

Table 1. Comparison of baseline data between success group and failure group.

Variables	Total (n = 360)	Success group (n = 295)	Failure group (n = 65)	Statistic	p
Age (years), mean ± SD	69.78 ± 4.47	69.72 ± 4.53	70.06 ± 4.22	$t = -0.55$	0.58
BMI (kg/m^2), mean ± SD	25.71 ± 2.92	25.62 ± 2.82	26.12 ± 3.32	$t = -1.26$	0.21
Intraoperative blood loss (mL), mean ± SD	219.06 ± 80.36	216.87 ± 78.98	229.00 ± 86.30	$t = -1.10$	0.27
Femoral cortical thickness index, mean ± SD	0.44 ± 0.09	0.45 ± 0.09	0.39 ± 0.08	$t = 4.45$	<0.01
Time since menopause (years), M (Q_1, Q_3)	14.00 (12.00, 17.00)	14.00 (12.00, 18.00)	13.00 (12.00, 17.00)	Z = −0.25	0.81
BMD T-score, M (Q_1, Q_3)	−3.06 (−3.32, −2.83)	−3.01 (−3.27, −2.80)	−3.23 (−3.45, −3.09)	Z = −4.83	<0.01
Operative time (min), M (Q_1, Q_3)	110.00 (84.00, 135.00)	109.00 (84.00, 133.00)	117.00 (85.00, 137.00)	Z = −1.08	0.28
Lateral wall thickness (mm), M (Q_1, Q_3)	24.40 (20.90, 27.30)	24.90 (21.40, 27.75)	22.20 (19.10, 24.40)	Z = −4.78	<0.01
Residence, n (%)				$\chi^2 = 0.23$	0.63
Urban	151 (41.94)	122 (41.36)	29 (44.62)		
Rural	209 (58.06)	173 (58.64)	36 (55.38)		
Injury mechanism, n (%)				$\chi^2 = 0.04$	0.83
High-energy	187 (51.94)	154 (52.20)	33 (50.77)		
Low-energy	173 (48.06)	141 (47.80)	32 (49.23)		
Hypertension, n (%)				$\chi^2 = 0.19$	0.66
No	230 (63.89)	190 (64.41)	40 (61.54)		
Yes	130 (36.11)	105 (35.59)	25 (38.46)		
Diabetes, n (%)				$\chi^2 = 0.56$	0.46
No	252 (70.00)	209 (70.85)	43 (66.15)		
Yes	108 (30.00)	86 (29.15)	22 (33.85)		
Rheumatic disease, n (%)				$\chi^2 = 1.25$	0.26
No	319 (88.61)	264 (89.49)	55 (84.62)		
Yes	41 (11.39)	31 (10.51)	10 (15.38)		
Fracture side, n (%)				$\chi^2 = 0.00$	0.95
Right	176 (48.89)	144 (48.81)	32 (49.23)		
Left	184 (51.11)	151 (51.19)	33 (50.77)		
Fracture type, n (%)				$\chi^2 = 0.28$	0.87
31A1	130 (36.11)	105 (35.59)	25 (38.46)		
31A2	97 (26.94)	81 (27.46)	16 (24.62)		
31A3	133 (36.94)	109 (36.95)	24 (36.92)		
Intramedullary nail position, n (%)				$\chi^2 = 19.31$	<0.01
Centrally positioned	303 (84.17)	260 (88.14)	43 (66.15)		
Eccentrically positioned	57 (15.83)	35 (11.86)	22 (33.85)		
Fracture reduction quality, n (%)				$\chi^2 = 19.10$	<0.01
Good	229 (63.61)	203 (68.81)	26 (40.00)		
Poor	131 (36.39)	92 (31.19)	39 (60.00)		
Posteromedial integrity, n (%)				$\chi^2 = 0.23$	0.63
Intact	162 (45.00)	131 (44.41)	31 (47.69)		
Not intact	198 (55.00)	164 (55.59)	34 (52.31)		

Abbreviations: BMD, bone mineral density; BMI, body mass index.

the predicted and observed probabilities, indicating good model calibration. The apparent calibration slope of the model was 1.016 and the apparent calibration intercept was −0.003, both close to the ideal values of 1 and 0, respectively. After bootstrap internal validation (1000 resamples), the optimism-corrected calibration slope was 0.977 (95% CI: 0.800–1.235) and the corrected calibration intercept was 0.005 (95% CI: −0.040 – 0.038). The bootstrap-corrected calibration curve closely aligned with the ideal calibration line (Fig. 2). Decision curve analysis showed that the predictive model outperformed both the "treat-all" and "treat-none" strategies across a threshold probability range of approximately 10% to 55%. Within this range, the model demonstrated stable and clinically meaningful net benefit (Fig. 3).

Discussion

In this study, risk factors associated with internal fixation failure were systematically evaluated in a retrospective analysis of postmenopausal patients undergoing surgery for osteoporotic intertrochanteric fractures. The results showed that poor fracture reduction quality and eccentric intramedullary nail position were independent risk factors for internal fixation failure, whereas higher BMD T-score,

Table 2. Univariate logistic regression analysis of internal fixation failure.

Variables	β	S.E	Z	*p*	OR (95% CI)
Residence					
Urban					1.00 (Reference)
Rural	−0.13	0.28	−0.48	0.63	0.88 (0.51 ~ 1.50)
Injury mechanism					
High-energy					1.00 (Reference)
Low-energy	0.06	0.27	0.21	0.83	1.06 (0.62 ~ 1.81)
Hypertension					
No					1.00 (Reference)
Yes	0.12	0.28	0.44	0.66	1.13 (0.65 ~ 1.97)
Diabetes					
No					1.00 (Reference)
Yes	0.22	0.29	0.75	0.46	1.24 (0.70 ~ 2.20)
Rheumatic disease					
No					1.00 (Reference)
Yes	0.44	0.39	1.11	0.27	1.55 (0.72 ~ 3.34)
Fracture side					
Right					1.00 (Reference)
Left	−0.02	0.27	−0.06	0.95	0.98 (0.57 ~ 1.68)
Fracture type					
31A1					1.00 (Reference)
31A2	−0.19	0.35	−0.53	0.60	0.83 (0.42 ~ 1.66)
31A3	−0.08	0.32	−0.25	0.81	0.92 (0.50 ~ 1.72)
Intramedullary nail position					
Centrally positioned					1.00 (Reference)
Eccentrically positioned	1.34	0.32	4.20	<0.01	3.80 (2.04 ~ 7.09)
Fracture reduction quality					
Good					1.00 (Reference)
Poor	1.20	0.28	4.23	<0.01	3.31 (1.90 ~ 5.76)
Posteromedial integrity					
Intact					1.00 (Reference)
Not intact	−0.13	0.27	−0.48	0.63	0.88 (0.51 ~ 1.50)
Age (years)	0.02	0.03	0.55	0.58	1.02 (0.96 ~ 1.08)
Time since menopause (years)	−0.01	0.03	−0.35	0.73	0.99 (0.93 ~ 1.05)
BMD T-score	−2.14	0.46	−4.62	<0.01	0.12 (0.05 ~ 0.29)
BMI (kg/m^2)	0.06	0.05	1.26	0.21	1.06 (0.97 ~ 1.16)
Operative time (min)	0.00	0.00	0.88	0.38	1.00 (1.00 ~ 1.01)
Intraoperative blood loss (mL)	0.00	0.00	1.10	0.27	1.00 (1.00 ~ 1.01)
Femoral cortical thickness index	−0.69	0.16	−4.22	<0.01	0.50 (0.36 ~ 0.69)
Lateral wall thickness (mm)	−0.18	0.04	−4.70	<0.01	0.84 (0.78 ~ 0.90)

Abbreviations: OR, odds ratio.

Table 3. Multivariate logistic regression analysis of internal fixation failure.

Variables	β	S.E	Z	*p*	OR (95% CI)
Intramedullary nail position					
Centrally positioned					1.00 (Reference)
Eccentrically positioned	0.87	0.38	2.28	0.02	2.38 (1.13 ~ 5.01)
Fracture reduction quality					
Good					1.00 (Reference)
Poor	1.12	0.33	3.38	<0.01	3.07 (1.60 ~ 5.87)
BMD T-score	−1.77	0.52	−3.41	<0.01	0.17 (0.06 ~ 0.47)
Femoral cortical thickness index	−0.61	0.19	−3.25	<0.01	0.54 (0.38 ~ 0.79)
Lateral wall thickness (mm)	−0.19	0.04	−4.35	<0.01	0.83 (0.76 ~ 0.90)

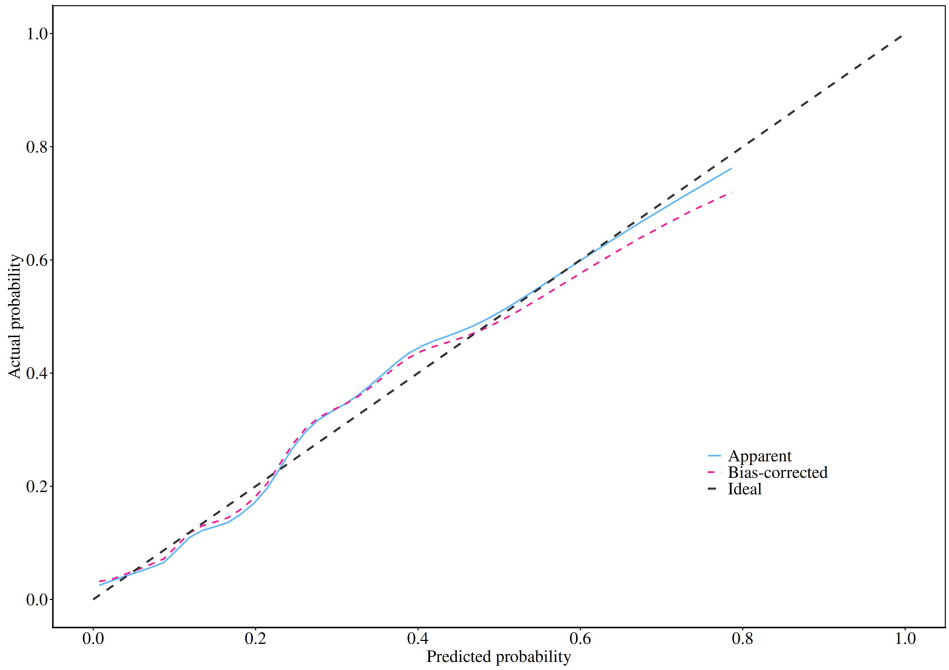


Fig. 2. Calibration curve of the predictive model.

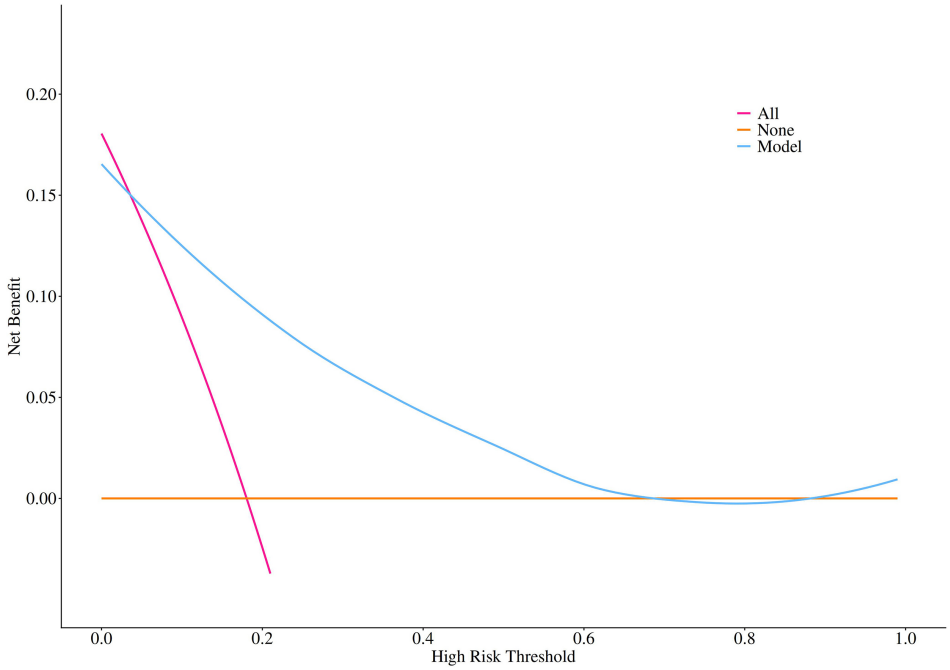


Fig. 3. Decision curve analysis of the predictive model.

greater femoral cortical thickness index, and greater lateral wall thickness were independent protective factors. The predictive model based on these variables demonstrated good discrimination, calibration and clinical utility, providing a reliable evidence-based foundation for clinical decision-making. This model is intended for immediate postoperative risk stratification rather than preoperative planning, as two of the independent predictors (fracture reduction quality and intramedullary nail position) can only be determined intraoperatively.

BMD T-score was found to be an independent protective factor for internal fixation failure in this study, a result consistent with previous studies. Due to decreased estrogen levels in postmenopausal women with osteoporosis, osteoclast activity is enhanced, resulting in thinning and fragmentation of bone trabeculae with reduced connectivity, as well as bone cortex thinning and increased porosity, thereby leading to a significant decline in the overall mechanical properties of bone [2,15]. Under such compromised bone quality, even with optimal positioning of the internal fixa-

tor, the screw–bone interface provides insufficient holding strength, making it difficult to achieve ideal fixation, and screw cutting/cut-out is more likely to occur during early postoperative weight-bearing [13,14]. Low bone mineral density may contribute to an increased risk of internal fixation failure in patients with osteoporotic proximal femoral fractures [16], and osteoporosis is the strongest predictor of postoperative mechanical complications of femoral intertrochanteric fractures, which can increase the risk by 3 to 5 times [17]. Therefore, for patients with severely reduced bone mineral density, the risk of internal fixation failure should be fully evaluated before surgery [18], and bone cement reinforced screw channels can be considered as an alternative, if necessary.

Femoral cortical thickness index is another important index of the quality of proximal femoral cortical bone. In this study, patients in the failure group had a significantly lower femoral cortical thickness index than those in the success group. A decreased femoral cortical thickness index reflects thinning of the proximal femoral cortical bone and widening of the medullary cavity. This not only weakens the bone's intrinsic mechanical bearing capacity but also reduces the fit between the intramedullary nail and the medullary cavity, thereby increasing the risk of nail motion or displacement [19]. In a study of 209 patients over 65 years old with intertrochanteric fracture, Polat et al. [20] found that the femoral cortical thickness index of the fractured side was significantly lower than that of the healthy side, and the proportion of Dorr C type medullary cavity (the thinnest cortex and the widest medullary cavity) in the fractured side was significantly higher than that in the healthy side, suggesting that bone morphological changes were closely related to fracture occurrence and internal fixation stability. The weak cortical bone could hardly provide adequate support, and it is easy to cause coxa vara and internal fixation failure under the action of muscle contraction and weight load following operation. Clinically, in patients with a low femoral cortical thickness index, an intramedullary nail with a diameter that more closely matches the medullary cavity should be selected intraoperatively whenever possible, and the main nail should be positioned centrally within the medullary cavity to optimize the mechanical conduction path [21]. In addition, some studies suggest that weight-bearing should be appropriately delayed in such patients to reduce the risk of early fixation failure.

The thickness of the lateral wall is a key anatomical factor affecting the stability of internal fixation of intertrochanteric fractures. In this study, patients in the failure group had significantly smaller lateral wall thickness than those in the success group. The lateral wall of the femur plays a key role as the "lateral baffle". A complete and strengthened lateral wall can effectively resist rotation and cutting stress of the head of the nail. The prospective study by Palm et al. [22] reported that the reoperation rate within 6 months was only 3% in patients with intact lateral wall after surgery, compared with as high as 22% in those with lateral wall fractures. Gotfried [23] proposed the concept of lateral wall and emphasized its crucial role in maintaining fracture stability. When the lateral wall is weak, the femoral head–neck block lacks lateral support, and the stress of the internal fixation is concentrated on the implant, thereby raising the risk of cut-out or cut-through. Hsu et al. [24] further quantified this index and identified a lateral wall thickness of <20.5 mm as an independent risk factor for PFNA internal fixation failure. Therefore, accurate preoperative evaluation of lateral wall thickness is of great value for surgical planning and prognostic assessment.

Procedural factors also play an important role in the occurrence of internal fixation failure. In this study, poor fracture reduction quality was found to be one of the strongest independent risk factors for internal fixation failure. Good fracture reduction is fundamental to the success of internal fixation. Only by restoring the normal anatomical relationship and force line structure of the proximal femur can the internal fixator exert its due biomechanical advantages [25]. As one of the indicators of poor reduction quality, separation and displacement of the coxa vara or fracture end can significantly alter the mechanical conduction path, impose abnormally high stress on the internal fixation device, and increase the risk of fatigue fracture and cut-through [26]. A previous study has also confirmed that poor reduction quality is an important predictor of postoperative mechanical complications of intertrochanteric fractures [11]. Therefore, anatomic or nearly anatomic reduction should be achieved as much as possible during operation. For irreducible fractures, limited open reduction can be considered to avoid sacrificing reduction quality for the pursuit of a minimally invasive approach.

The intramedullary nail position of the intramedullary nail is another key surgical technical factor. In this study, patients with a poorly positioned main nail (deviation from the center of the medullary cavity) were at a significantly increased risk of internal fixation failure. The intramedullary nail is designed to conduct mechanical loads through the center of the medullary cavity, so that the stress is evenly distributed in the proximal femur. Deviation of the main nail from the medullary cavity center can alter the mechanical conduction path and elevate the risk of stress concentration at the nail-bone interface, thus leading to local bone resorption, screw loosening and even main nail fracture [27]. In addition, suboptimal positioning of the main nail is often accompanied by the unsatisfactory position of the helical blade or lag screw in the femoral head, thus affecting key parameters such as tip–apex distance and femoral distance [28]. Therefore, accurate positioning should be performed under fluoroscopic guidance to ensure that the main nail is centrally positioned within the medullary cavity with appropriate insertion depth.

The prediction model constructed in this study showed good discriminative ability, calibration and clinical utility (DCA curve showed significant net benefit), indicating that the

model can effectively identify patients at high risk of internal fixation failure. However, several limitations of this study should be acknowledged. First, the study adopts a single-center retrospective design with a relatively limited sample size (360 patients, including 65 in the failure group). Although bootstrap internal validation (1000 resamples) with optimism correction was performed to assess potential overfitting, external validation using an independent cohort from another institution is lacking. Therefore, the generalizability of our predictive model to other populations requires further investigation. The relatively high proportion of high-energy injuries in this cohort differs from the typical injury pattern of osteoporotic intertrochanteric fractures, which predominantly occur following low-energy trauma. This finding may reflect differences in patient selection or injury mechanism classification and should be considered when interpreting the generalizability of our findings. Second, the postoperative follow-up period in this study was only 6 months. Although the vast majority of internal fixation failures occur in the early postoperative period (within 6 months after surgery), some delayed complications, such as long-term internal fixation fatigue and fracture nonunion requiring surgical intervention after long-term conservative treatment, may not be fully captured within the 6-month follow-up window. Therefore, this study could not evaluate the long-term incidence of internal fixation failure and long-term functional prognosis, and further studies are necessary to extend the follow-up period to fully evaluate internal fixation failure and its impact on the long-term quality of life of patients. Third, due to data limitations, the study did not include detailed information on postoperative weight-bearing timing, rehabilitation protocols, or follow-up management, which may have introduced residual confounding (e.g., weight-bearing time, adherence to rehabilitation exercises, and regular follow-up), which may also have a potential impact on implant failure. Future studies should prospectively incorporate detailed information on surgeon-related factors and postoperative rehabilitation to facilitate a more comprehensive evaluation of the multi-dimensional risk factors of internal fixation failure.

Conclusions

In this retrospective analysis, risk factors for internal fixation failure were systematically evaluated based on 360 postmenopausal patients with osteoporotic intertrochanteric fractures who underwent intramedullary nail fixation. The failure rate of internal fixation was 18.06%. Multivariate logistic regression analysis showed that fracture reduction quality, deviation of the intramedullary nail from the center of the medullary cavity, bone mineral density, femoral cortical thickness index, and lateral wall thickness were independent predictors of internal fixation failure in postmenopausal patients with osteoporotic intertrochanteric fractures after intramedullary nail internal fixation. A predictive model incorporating these independent risk factors demonstrates excellent discriminative performance, as well as good calibration and clinical utility. Moreover, it provides substantial net clinical benefit across a broad range of threshold probabilities, indicating its ability to effectively identify patients at high risk of internal fixation failure. The aforementioned risk factors should be given a high level of attention in clinical settings, where comprehensive postoperative assessment of bone quality, anatomical fracture reduction, and intraoperative affirmation of the main nail's central positioning in the medullary cavity should be conducted to reduce the risk of internal fixation failure and improve patient prognosis.

Availability of Data and Materials

The data analyzed are available from the corresponding author upon reasonable request.

Author Contributions

YSY and SXW designed the research study. YSY, HTL and SXW performed the research. ZKJ, SLZ and YYL analyzed the data. YSY drafted the article. All authors have been involved in revising the manuscript critically for important intellectual content. All authors gave final approval of the version to be published. All authors have participated sufficiently in the work to take public responsibility for appropriate portions of the content and agreed to be accountable for all aspects of the work in ensuring that questions related to its accuracy or integrity.

Ethics Approval and Consent to Participate

This study obtained approval from the Ethics Committee of The Second Affiliated Hospital of Liaoning University of Traditional Chinese Medicine (2024(XS)-011-02(FS)). All patients were informed of all possible clinical outcomes of the different treatments and signed a written informed consent. This study was conducted in strict accordance with the principles of the Declaration of Helsinki.

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Conflict of Interest

The authors declare no conflict of interest.

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