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Original Article

Predictive value of a prediction system based on bone mineral density and proximal femoral imaging indexes for hip fracture risk in osteoporotic patients

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Abstract: Objective: To establish a nomogram model based on bone mineral density (BMD), and radiographic indexes of the proximal femur for predicting hip fracture (HF) risk in osteoporosis patients. Methods: A total of 120 patients who underwent both orthopedic and lateral view examination from February 2022 to January 2024 were retrospectively collected and screened. They were divided into fracture (n=60) and non-fracture groups (n=60). The recorded parameters included sex, age, femoral intertrochanteric BMD, femoral cortical thickness (FCT), femoral neck length (FNL), hip axis length (HAL) and the hip offset distance (FO). Univariate and multivariate logistic regression analysis were conducted to determine the risk factors for hip fracture in osteoporotic patients. A nomogram model was subsequently constructed. Furthermore, to validate the model's clinical utility, an additional 1-year follow-up was conducted on 40 randomly selected patients. Results: The fracture group had significantly longer HAL, thinner FCT, and reduced femoral intertrochanteric BMD than the non-fracture group (all $P < 0.001$). The HAL, FCT and intertrochanteric BMD were the independent risk factors for the hip fracture. The model accurately predicted hip fracture in osteoporosis patients, with an Area under the curve (AUC) of 0.93, sensitivity of 0.86 and specificity of 0.83. During a one-year follow-up of 40 osteoporosis patients, 6 fractures were observed, 5 with a prediction model score > 100 and 1 with a score < 100, further validating the reliability of the predictive model. Conclusion: The nomogram model has a better prediction ability of hip fracture risk in osteoporosis patients. It provides a theoretical basis for the individualization of the diagnosis and treatment for elderly patients.

Keywords: Line drawing, bone mineral density, osteoporosis, hip, fracture, risk factors

Introduction

Osteoporosis is the most common disease of abnormal bone metabolism, characterized by pathologic changes such as decreased bone mineral density (BMD), destruction of bone microstructure, and increased bone fragility, which leads to reduced bone quality and increased fracture risk [1]. Hip fractures account for more than 50% of osteoporotic fractures in the elderly, with the highest morbidity, mortality and associated medical costs [2]. It has been reported that the morbidity and mortality within 1 year after hip fracture can be as high as 14%-36% [3]. Clarifying the association between hip fracture and osteoporosis in the elderly is crucial for the subsequent development of precise rehabilitation plans and the rational implementation of anti-osteoporosis treatment.

Currently, dual-energy X-ray absorptiometry (DXA) is considered the gold standard for osteoporosis diagnosis and an important method for evaluating bone health and predicting fractures [4]. However, patients with hip fractures

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have limited mobility, and DXA is cumbersome to perform and associated with certain costs. Moreover, due to limited equipment availability and the cumbersome nature of the test, it is clinically challenging to perform DXA for all patients with hip trauma. Additionally, DXA has limitations in evaluating bone microstructure and is easily affected by bone size, osteophytes, and abdominal aortic calcification [5]. It cannot characterize trabecular microstructural features such as morphology, quantity, and connectivity - factors that play a critical role in bone mechanical strength and fracture resistance. Therefore, relying solely on DXA to determine bone strength and predict potential fracture risk has inherent limitations in sensitivity and accuracy.

X-ray examination is the most common imaging method, based on data from gross morphological characteristics of bones. In recent years, scholars have explored osteoporosis assessment by measuring hip-related anatomical and morphological parameters derived from X-ray images. The cortical thickness index (CTI) reflects the overall cortical bone thickness of the proximal femur; studies have shown that age-related thinning of femoral cortical bone reduces the proximal femur's load-bearing capacity, significantly increasing hip fracture risk [6]. Mean femoral neck length (MFNL) has also been found to correlate with fracture subtypes [7]. Hip axis length (HAL) approximates the femoral moment arm when the proximal femur is subjected to external forces; a longer moment arm requires less external force to cause a hip fracture, making increased HAL a risk factor for hip fracture [8]. Femoral offset (FO) represents the moment arm of the hip abductor muscles, which exert a significant influence on stress transmission in the proximal femur. Bone biomechanical experiments have confirmed that a longer FO substantially increases bone load and elevates hip fracture risk [9, 10].

The aim of this study was to identify hip fracture risk factors by measuring and analyzing intertrochanteric BMD and proximal femoral imaging parameters in patients. Based on these identified risk factors, a nomogram model was established to assess hip fracture risk in the osteoporotic population, thereby providing guidance for clinical decision-making.

Materials and methods

Inclusion criteria: (1) BMD T-score ≤ -2.5 SD (according to the 1994 WHO diagnostic criteria for osteoporosis); (2) clear history of hip trauma; (3) clear consciousness and ability to cooperate with screening; (4) standardized pre- and post-hip X-rays; (5) fracture group: meet the diagnostic criteria for hip fracture.

Exclusion criteria: (1) age < 65 years; (2) severe high-energy injury or pathological fracture; (3) history of other hip disorders; (4) thyroid disease, autoimmune disease, severe hepatic or renal insufficiency, and/or long-term use of drugs affecting bone resorption; (5) psychiatric or communication disorders; (6) incomplete clinical or imaging data.

General information

A total of 120 patients with traumatic osteoporosis who received treatment at Dongying People's Hospital from February 2022 to January 2024 were collected, equally divided into the fracture group (n=60) and non-fracture group (n=60). The influencing factors included gender, age, height, body mass, BMD, and X-ray-derived proximal femoral imaging parameters (femoral cortical thickness [FCT], femoral neck length [FNL], hip axis length [HAL] and the hip offset distance [FO]).

Ethics approval statement: This study was approved by the Ethics Committee of Dongying People's Hospital (Approval No.: 2025-012).

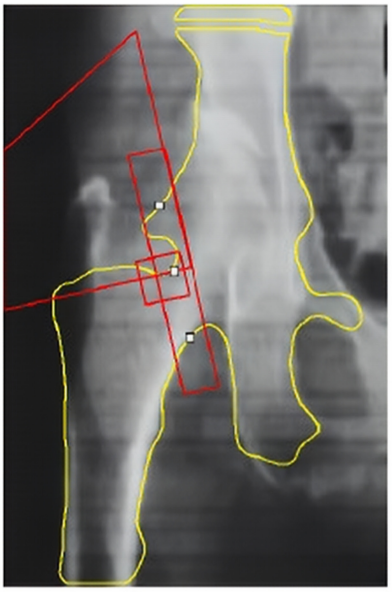
Patient and public involvement statement

No patients or members of the public were involved in the design, implementation, reporting, or dissemination of this study.

Measurement methods

BMD testing: All patients underwent BMD measurement using a Kanda Intercontinental (KD-GRAND) dual-energy X-ray absorptiometer. The measured sites included the femoral neck, femoral Ward's triangle, femoral intertrochanteric region, and total femur. The primary study variable was femoral intertrochanteric BMD, with diagnoses categorized as follows: normal (T-score > -1.0), osteopenia (-1.0 ≥ T-score >

A



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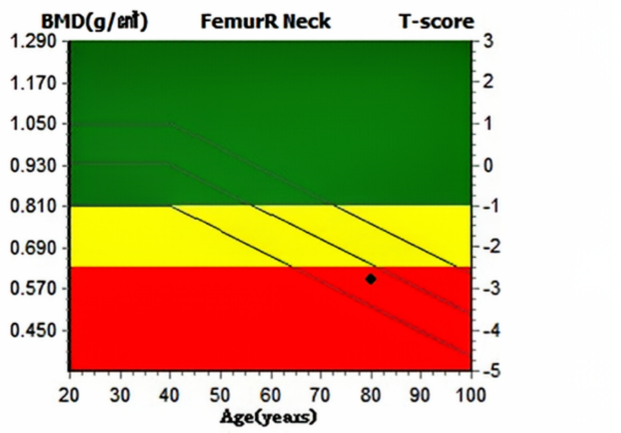

C

Region	BMD	T-score	Z-score	YA(%)	AM(%)
Neck	0.592	-2.8	-0.4	64	93
Wards	0.590	-1.9	0.7	67	121
G.T.	0.668	-0.8	1.3	88	126
Total	0.605	-2.3	0.1	62	86

Figure 1. Dual-energy X-ray bone mineral density testing of the hip. A. The image shows the region of interest (ROI). In the image, red boxes outline the femoral neck, ward's triangle, and the greater trochanter, while a yellow box outlines the total hip. B. On the graph, the horizontal axis represents age, the left Y-axis represents bone mineral density (BMD, g/cm^2), and the right Y-axis shows the T-score. The green zone indicates normal bone density (T-score ≥ -1.0), the yellow zone indicates osteopenia (-2.5 < T-score < -1.0), and the red zone indicates osteoporosis (T-score ≤ -2.5). C. T-score: Compares an individual's bone mineral density (BMD) to the average peak BMD of a healthy young adult of the same sex. Z-score: Compares an individual's BMD to the average BMD of people of the same age, sex, and body size. YA (%): Percentage of the average BMD for a healthy young adult. AM (%): Percentage of the average BMD for your age group. GT: Greater Trochanter.

-2.5), osteoporosis (T-score ≤ -2.5), or severe osteoporosis (T-score ≤ -2.5 with concurrent fracture) (**Figure 1**).

Measurement of proximal femoral imaging parameters: Patients were placed in a supine position on the imaging table with both lower limbs extended, feet internally rotated, and knees adducted. Standard anteroposterior plain radiographs of both hips were acquired using a DR digital radiography system (UNIFILM, COL-R-AF01, China). Radiographs with incorrect positioning were excluded. Eligible images were processed using the Medical Imaging Archive and Transmission System (GE Healthcare, USA) with its built-in measurement software. All parameters were independently measured by two junior radiologists (with > 5 years of diagnostic experience) and reviewed by a senior radiologist (with > 15 years of diagnostic experience). For patients with hip fracture, measurements were performed on the unaffected side.

Femoral cortical thickness (FCT): A straight line perpendicular to the mid-axis of the femoral shaft was drawn 5 cm from the intersection of the cortex at the inferior border of the lesser trochanter and the femoral cortex. The distances between this line and the intersections of the lateral and medial femoral shaft cortices were measured, and the difference between these two distances was defined as FCT. As shown in **Figure 2A**, FCT = AD - BC.

Femoral neck length (FNL): The mid-axis lines of the femoral neck and femoral shaft were drawn. The distance from the intersection of their extension lines to the center of the femoral head was measured as FNL (**Figure 3**).

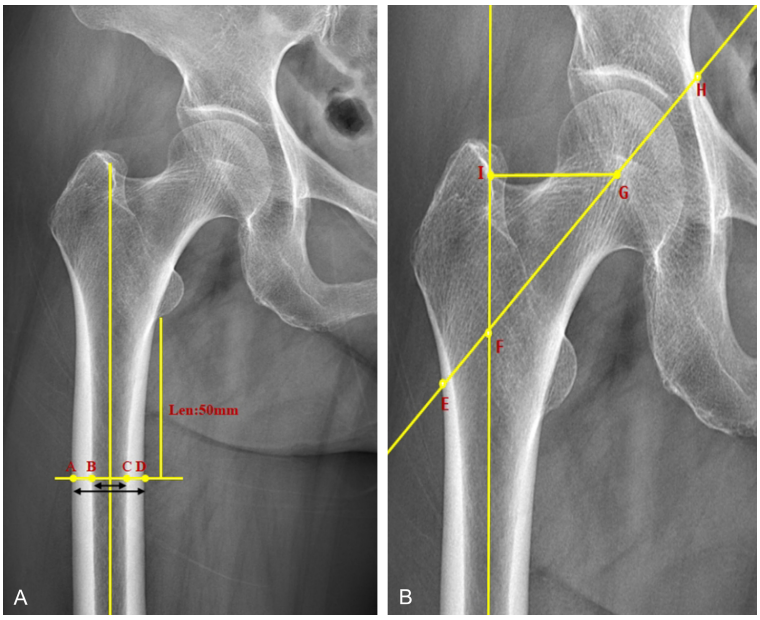

Figure 2. Combined schematic of femoral anatomical parameters. A. FCT: Alignment of the femoral stem relative to anatomical axes (not pictured, see methods). B. Anatomical hip measurements. FNL: Measured as the distance from the intersection of the femoral neck mid-axis (FG) and femoral stem mid-axis (point G) to the femoral head center (F). HAL: Linear distance between the pelvic inner edge (E) and femoral outer edge (H), defined by extending the femoral neck axis. FO: Vertical distance (IG) from the femoral head center (F) to the femoral stem axis.

Hip axis length (HAL): The axis of the femoral neck was extended to the inner edge of the pelvis and the outer edge of the femur; the distance between these two points was defined as HAL (**Figure 2B**).

Femoral offset (FO): The vertical distance between the center of the femoral head and the axis of the femoral shaft (**Figure 2B**).

Data analysis and modeling: Statistical analysis of the study population was performed using SPSS 27.0. Count data were expressed as rates or percentages, with comparisons of group differences using the chi-square test. Normally distributed measurement data were expressed as mean ± standard deviation, and comparisons between two independent groups were performed using the t-test. Risk factors for hip fracture were screened by univariate logistic regression analysis, and variables with statistically significant differences in univariate analysis were included in multivariate logistic regression analysis. A nomogram prediction model was established based on the identified independent risk factors for hip fracture. The performance of the prediction model was evaluated using calibration curves, receiver operating characteristic (ROC) curves, and decision curve analysis (DCA) curves. A *P*-value < 0.05 was considered statistically significant.

Results

Comparison of general information

As shown in **Table 1**, no significant differences were found in terms of sex, age, femoral neck length or femur cortical thickness.

Risk factors for hip fracture

Univariate and multivariate logistic regression analyses revealed that X-ray-derived FCT, HAL, and BMD exhibited statistically significant differences between the two groups ($P < 0.001$). These three parameters were identified as independent risk factors for hip fracture in osteoporotic individuals. Relevant risk factors for hip fracture are summarized in **Table 2** (univariate analysis) and **Table 3** (multivariate analysis).

Construction of a nomogram for predicting hip fracture risk in middle-aged and elderly patients

Based on the logistic regression results, three independent risk factors associated with hip fracture risk in osteoporotic patients were identified, and a nomogram was constructed to predict hip fracture risk in this population (**Figure 3**). The predictive performance of the model was evaluated using ROC curves, which yielded an area under the curve (AUC) of 0.93, indicating good discriminative ability (**Figure 4**). The calibration curve demonstrated high consistency between the predicted hip fracture risk and the actual incidence in osteoporotic patients (**Figure 5**). The DCA curve confirmed that the nomogram was a reliable predictive model for assessing hip fracture risk and provided greater net benefits for clinical decision-making across a wide range of threshold probabilities (**Figure 6**).

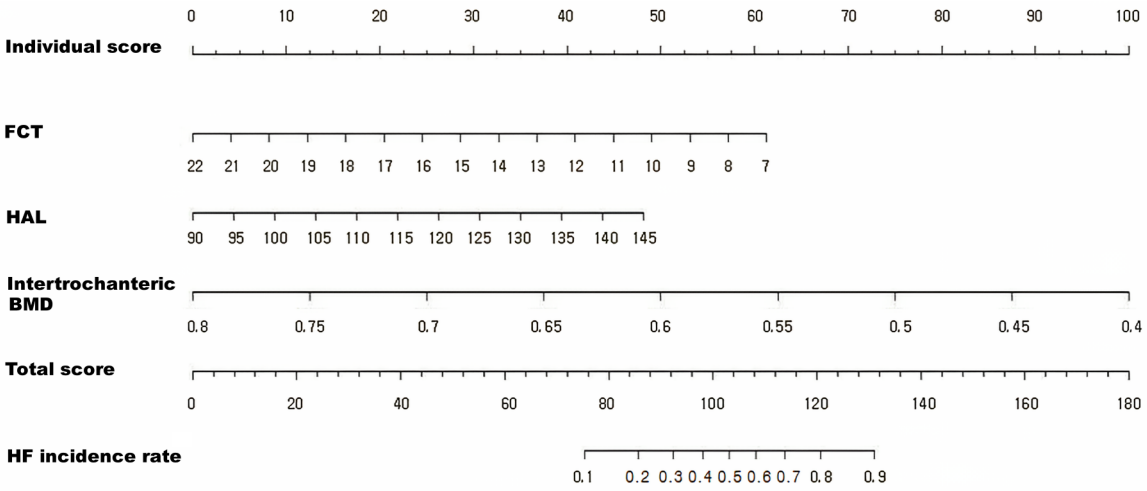

Figure 3. Column line diagram of the risk of hip fracture in osteoporotic patients.

Table 1. General information

Clinical and imaging data		Fracture group (n=60)	Non-fracture group (n=60)	χ^2	*p*-value
Age		77.67±7.76	75.67±9.81	19.74	0.90
Sex	Male	22 (36.67%)	31 (51.67%)	2.16	0.14
	Female	38	29		
Femoral neck length (mm)		54.74±7.59	53.42±7.71	0.95	0.35
Femur cortical thickness (mm)		14.03±2.91	15.56±2.76	2.97	< 0.001
Hip axis length (mm)		122.05±12.72	112.06±8.19	5.11	< 0.001
Hip offset distance (mm)		41.68±4.97	40.82±5.59	-0.89	0.38
Femoral intertrochanteric bone mineral density (g/ml)		0.5338±0.08	0.6757±0.074	9.87	< 0.001

Table 2. Single factor logistic regression analysis affecting fracture

Variable	β	SE	Wald	*P* value	OR	Lower 95% CI	Upper 95% CI
X-ray femoral neck length (mm)	0.023	0.024	0.896	0.344	1.023	0.976	1.073
X-ray femoral cortical thickness (mm)	-0.193	0.069	7.818	0.005	0.825	0.721	0.944
X-ray hip axis length (mm)	0.086	0.020	18.270	< 0.001	1.090	1.048	1.133
X-ray hip deviation (mm)	0.031	0.035	0.792	0.374	1.032	0.963	1.105
Inter-rotor bone density (g/ml)	-18.412	3.017	37.246	< 0.001	1.089E-9	2.728E-11	3.731E-6

Table 3. Multiple factor logistic regression analysis affecting fracture

Variable	β	S.E.	Wald	*P* value	OR	Lower 95% CI	Upper 95% CI
X-ray femoral cortical thickness (mm)	-0.361	0.117	9.542	0.002	0.697	0.554	0.877
X-ray hip axis length (mm)	0.093	0.028	10.767	0.001	1.098	1.038	1.160
Inter-rotor bone density (g/ml)	-21.434	4.018	28.460	< 0.001	4.913E-10	1.868E-13	1.292E-6

Discussion

Hip fracture in the elderly is the most severe type of osteoporotic fracture, with extremely high disability and mortality rates [1]. The disability rate of hip fracture in the elderly is approximately 50%, and the morbidity and mortality within 1 year after fracture range from

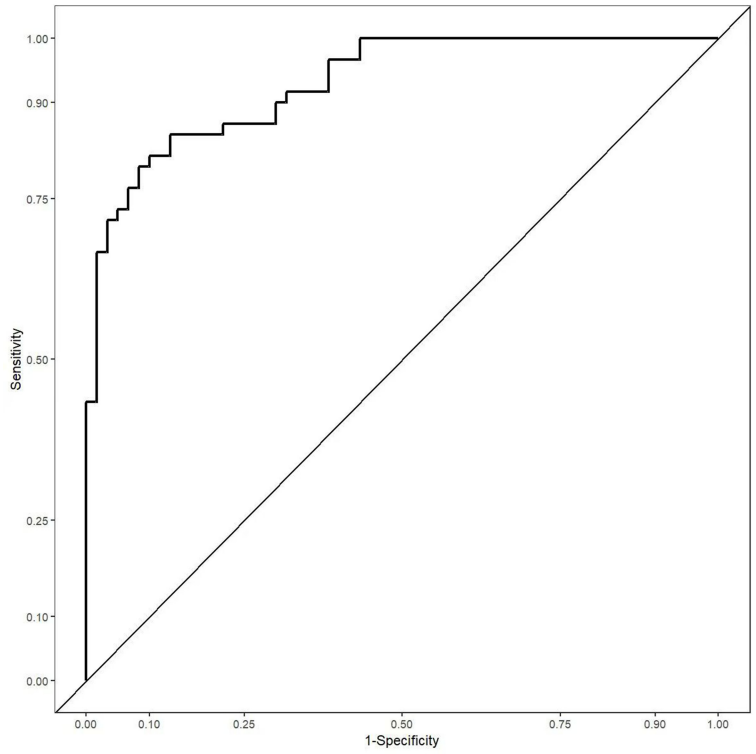

Figure 4. ROC curves analyzing the predictive value of the above column-line diagram model for hip fracture risk.

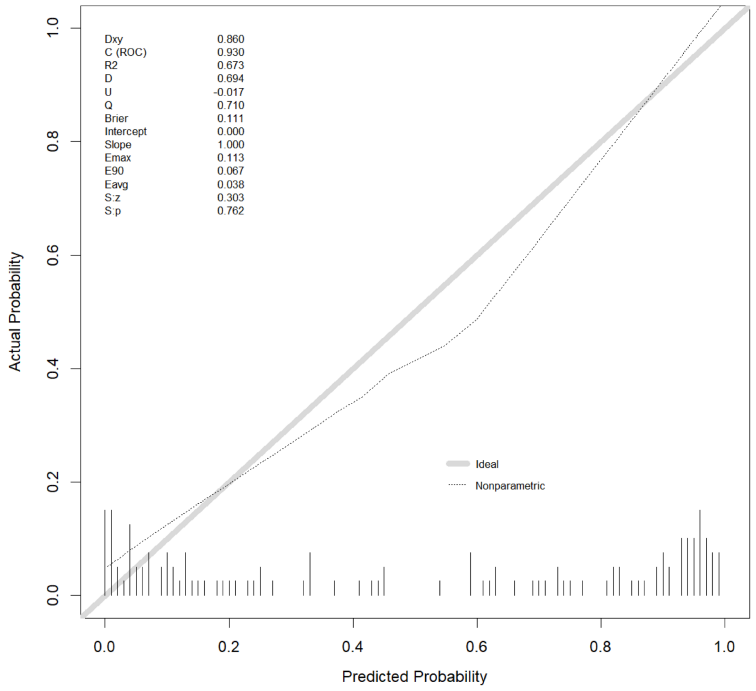

Figure 5. Calibration curve.

14% to 36% [3]. Due to the progressive deterioration of various physical functions in the elderly, who often have one or more underlying diseases, the risk of developing a series of complications is increased. This imposes a heavy economic and psychological burden on patients and seriously impairs their physical function and quality of life. Early, timely, and effective prediction of hip fracture in the elderly is therefore particularly important, and establishing an effective risk prediction model is of great significance. In our study, we analyzed data from 60 patients with hip fracture and identified age, gender, intertrochanteric BMD, FCT, FNL, HAL, and FO as independent risk factors for hip fracture. Based on these factors, we constructed a nomogram model to predict hip fracture risk in middle-aged and elderly individuals. Using this nomogram, clinicians can identify patients at risk of hip fracture and provide a basis for guiding preventive measures to avoid fracture occurrence.

Most previous studies have concluded that age and gender are independent risk factors for hip fracture [11]. This is because senile osteoporosis typically onsets after 70 years of age; with aging and the functional decline of cells, tissues, and organs, both cortical and trabecular bone are lost. In addition, reduced sunlight exposure and physical activity with age compromise bone quality and increase the risk of hip fracture. Female gender is also an independent risk factor for hip fracture. Elderly female patients experience age-related declines in physiological function, a sharp reduction in estrogen levels, and subsequent bone loss, all of which increase hip fracture risk. Studies have shown that after meno-

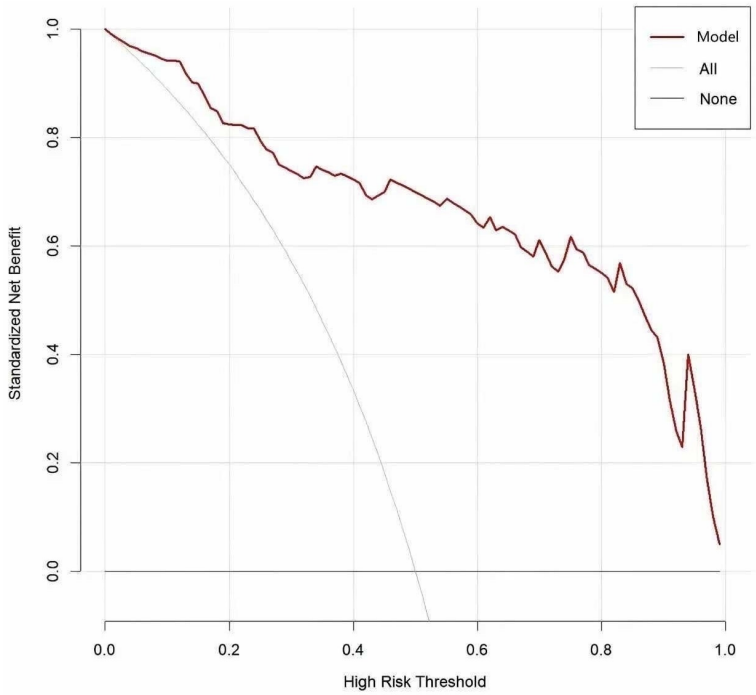

Figure 6. Clinical decision curve (DCA curve).

pause, as ovarian function and estrogen levels gradually decrease, osteoclastic bone resorption gradually exceeds osteoblastic bone formation, leading to increasingly severe bone loss. The longer the postmenopausal period, the higher the risk of osteoporotic fracture. However, in the present study, we found no strong correlation between age, gender, and hip fracture occurrence. This may be attributed to the retrospective nature of the study and potential selection bias in the enrolled cases.

In the present study, decreased bone density was identified as an independent risk factor for hip fracture. Bone density mainly reflects bone toughness; a reduction in bone density causes cortical bone thinning, severe impairment of compressive capacity, and a significant increase in bone fragility, thereby elevating fracture risk [12]. Previous studies have shown that reduced bone density in osteoporosis triggers bone remodeling to ensure the hip can bear pressure loads. With further bone loss, the proximal femur exhibits altered force distribution, and the morphology and density of bone tissue are insufficient to withstand excessive stress and deformation, leading to increased fracture risk [13]. After the onset of osteoporosis, the body's bone mass and density decrease, causing cortical bone thinning, a marked increase in bone fragility, and a significant reduction in bone strength. This severely impairs the bone's pressure resistance, further increasing fracture risk [12]. To maintain the hip's load-bearing capacity, bone remodeling occurs in osteoporotic patients, which may alter the force direction of the hip. Bone tissue then becomes unable to withstand greater stress and deformation, also contributing to increased fracture risk [13].

In the present study, FCT was found to be an independent risk factor for hip fracture. Previous studies have shown that changes in hip joint geometry influence fracture occurrence [14], which is consistent with our findings. Cortical bone is a key component of bone strength and an important supportive tissue for bone. After 65 years of age, bone mass decreases rapidly, accelerating cortical bone thinning and reducing bone quality and strength. The cortical bone of the femoral neck and lateral intertrochanteric region is the primary area bearing tensile forces; reduced cortical thickness in this region increases fracture susceptibility, so hip fracture risk rises significantly as femoral cortical thickness decreases. Previous studies have confirmed that hip fragility fractures are associated with proximal femoral cortical thickness, trabecular bone distribution, and hip geometry. Among these factors, the cortical thickness index can better assess hip cortical bone quality. Evaluating hip fracture risk in elderly individuals with high or low cortical bone content can improve understanding of bone mass, which is conducive to fracture prevention [15]. From a biomechanical perspective, the cortical bone of the proximal femur is the key area bearing mechanical stress. Finite element analysis shows that cortical bone thickness directly affects the Von Mises stress distribution of bone [16]. Thin cortical bone models (< 0.5 mm) exhibit stress concentration under low loads, with a fracture stress of only 51.6 MPa, and fracture lines are mainly distributed at the junction of the femoral neck base and lesser trochanter. Thick

cortical bone models (> 1.2 mm) can withstand up to 96.4 MPa, significantly delaying fracture occurrence. This difference is due to the role of cortical bone as a "mechanical support"; reduced thickness alters the stress transmission path of trabecular bone, leading to imbalanced stress distribution.

In addition, some scholars have assessed hip fracture risk by measuring hip-related anatomical and morphological parameters (CTI, HAL, FO) on X-ray images [17-20]. Kaptoge et al. [21] found a 1-fold higher risk of hip fracture for every one standard deviation increase in FNL. Parton et al. [22] found that FNL was significantly associated with intracapsular fractures. Biomechanically, when the hip impacts the ground during a fall, hip geometry affects the site of bone stress concentration, which can lead to fractures in different regions. A shorter femoral neck length, smaller neck-shaft angle, and shorter moment arm result in greater stress on the femoral neck, increasing the likelihood of femoral neck fracture. Conversely, a longer femoral neck length, larger neck-shaft angle, and longer moment arm increase stress on the lesser trochanter region, making intertrochanteric fracture more likely. FO is the moment arm of the hip abductor muscle group. Previous studies have identified it as an important factor affecting prosthesis geometry, a key reference index for restoring normal hip biomechanics, and an important factor in maintaining soft tissue balance. FO significantly affects stress transmission in the proximal femur, which may be related to proximal femoral fracture. A longer FO significantly increases bone load and elevates hip fracture risk. However, in this study, femoral neck length and FO were not identified as independent risk factors for hip fracture.

Domestic and international studies have also found that HAL can predict femoral neck fracture occurrence and is positively correlated with femoral neck fracture incidence. Crabtree et al. [23] found that for every one-standard deviation increase in HAL, the incidence of proximal femoral fracture in the elderly increased by 1.8-fold. When HAL increases, even minor impact forces (e.g., from a fall) can cause fracture due to the longer moment arm. Previous experiments have demonstrated that longer hip axis length and femoral offset are risk factors for hip fracture [24]. When the proximal femur is subjected to external force, HAL approximates the femoral moment arm; the longer the moment arm, the less external force is required to cause a hip fracture. These findings are highly consistent with our results, which confirm that HAL is an independent risk factor for hip fracture.

There are several imitations to this research. First, this study is retrospective, with potential selection bias. Second, the sample size is small and the case source is single; validation with large, multicenter samples is required. Third, the study includes relatively few research parameters; additional indicators such as other imaging parameters should be incorporated.

In conclusion, the combination of bone mineral density and proximal femoral imaging parameters has good predictive ability for hip fracture risk in osteoporotic patients. This approach provides a theoretical basis for the individualized diagnosis and treatment of elderly patients and assists in the prevention of hip fracture.

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Disclosure of conflict of interest

None.

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