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Original Article

Predictive value of nutritional status for delayed healing after open fracture of the extremities in the elderly: construction of a nomogram model

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Abstract: Objective: To evaluate the association between preoperative nutritional indicators and postoperative fracture healing outcomes in elderly individuals. Methods: A retrospective analysis was conducted on 221 patients aged 60 years or older who underwent surgery for open extremity fractures at Shanghai Sixth People's Hospital between March 2021 and November 2024. Patients were stratified into normal healing (n=139) and delayed healing (n=82) groups based on radiographic criteria at four months postoperatively. Preoperative nutritional status was assessed using BMI, albumin, prealbumin, hemoglobin, lymphocyte count, Mini Nutritional Assessment (MNA), Nutritional Risk Screening 2002 (NRS-2002), and Subjective Global Assessment (SGA). Statistical analyses included chi-square tests, independent samples t-tests, logistic regression, and receiver operating characteristic (ROC) curve analyses. Results: The incidence of delayed healing was 37.1%. BMI, albumin (P=0.006), prealbumin (P=0.014), hemoglobin (P=0.042), and MNA scores (P=0.029), and NRS-2002 scores (P=0.004) were significantly associated with healing outcome. Multivariate logistic regression identified BMI (OR=0.729, P=0.006), albumin (OR=0.933, P=0.040), prealbumin (OR=0.979, P=0.015), MNA (OR=0.933, P=0.020), and SGA (OR=0.478, P=0.033) as independent protective factors for normal healing; while lymphocyte count and NRS-2002 were independent risk factors. ROC analysis showed high predictive value for delayed healing using these markers (AUC=0.964), and an integrated nomogram model achieved high discriminative ability. Conclusion: Preoperative nutritional status, as evidenced by BMI, serum protein markers, and validated nutritional assessment scales, was significantly associated with postoperative fracture healing outcomes in elderly patients following open extremity fracture surgery.

Keywords: Open fractures, elderly patients, nutritional status, fracture healing, delayed union, prognostic factors

Introduction

Open fractures of the extremities are prevalent among elderly individuals, posing significant clinical and socioeconomic burdens globally [1]. With increasing life expectancy and improved healthcare, the incidence of traumatic fractures in older adults continues to rise [2]. These injuries involve direct communication between the fracture site and the external environment, leading to an elevated risk of infection, tissue damage, and impaired healing [3]. Despite advancements in surgical techniques and perioperative care, delayed fracture healing-defined as failure to achieve expected union within a standard timeframe - remains a critical challenge in geriatric trauma care [4].

Delayed healing after open fractures significantly compromises patient quality of life, prolongs hospital stays, and increases healthcare cost [5]. Bone repair involves complex biologic processes, including inflammation, cell proliferation, matrix synthesis, and remodeling [6]. In the elderly, age-related changes such as impaired angiogenesis, reduced proliferative capacity of mesenchymal stem cells, and diminished sensitivity to growth factors impede these reparative mechanisms [7]. Additionally, comorbidities like diabetes mellitus, vascular disease, and osteoporosis further exacerbate healing delays [8].

Nutritional status has emerged as a crucial determinant of bone healing potential. Elderly patients are particularly vulnerable to malnutrition due to chronic diseases, decreased appetite, poor absorption efficiency, and socioeconomic constraints [9]. Malnutrition impairs systemic immune function and resistance to infection while directly affecting bone metabolism by limiting essential substrates for collagen synthesis, osteoblast differentiation, and cellular proliferation at the injury site [10]. Deficiencies in protein and key micronutrients (e.g., vitamin D, calcium, zinc) have been independently linked to poor regenerative capacity and suboptimal outcomes [11].

Serological indices such as albumin, prealbumin, and hemoglobin levels, along with anthropometric measures like body mass index (BMI), serve as practical indicators of nutritional reserves and overall health status [12]. Standardized tools for comprehensive nutritional assessment - such as the Mini Nutritional Assessment (MNA), Nutritional Risk Screening 2002 (NRS 2002), and Subjective Global Assessment (SGA) - help identify at-risk individuals and guide targeted intervention. However, there is a lack of high-quality evidence directly linking nutritional status to delayed fracture healing outcomes in elderly patients with open extremity injuries [13].

Accurate risk stratification using reliable clinical and biochemical predictors is essential for guiding perioperative management and minimizing the burden of delayed healing [13]. Advanced statistical modeling, including nomogram construction, integrates multiple predictive factors into user-friendly platforms for individualized risk estimation [14]. Nomograms have been widelyvalidated in oncology and cardiovascular medicine and are increasingly used in orthopedics as evidence-based methods for making decisions [15]. Nevertheless, robust predictive tools tailored to elderly populations undergoing surgery for open fractures that incorporate nutritional status are lacking.

This study aimed to systematically investigate the relationship between preoperative nutritional status - reflected by objective serological markers and validated clinical assessment scales - and the risk of delayed healing after open extremity fractures in elderly patients. By retrospectively analyzing clinical, biochemical, and nutritional data and applying rigorous statistical approaches, including logistic regression and receiver operating characteristic (ROC) analysis, we aim to identify key nutritional factors associated with healing outcomes. Our secondary objective was to develop and internally validate a nomogram model for reliably predicting the risk of delayed healing, facilitating early intervention and personalized clinical management. Through this research, we aimed to provide a comprehensive evidence base supporting routine nutritional assessment in geriatric orthopedic practice, highlighting the multifaceted contributions of nutrition to skeletal repair, and predicting adverse outcomes. Integrating nutritional risk factors into orthopedic prognostication moves us towards a more holistic, patient-centered approach to fracture care in the elderly.

Patients and methods

Patient selection and criteria

A retrospective study was conducted on 221 elderly patients who underwent surgery for open fractures of the extremities at Shanghai Sixth People's Hospital from March 2021 to November 2024. Patients were categorized into two groups based on their healing status four months post-surgery: normal healing group (n=139) and delayed healing group (n=82). The criteria for diagnosing delayed fracture healing after surgery are as follows: A fracture is considered to have delayed healing if, by four months post-surgery, it has not healed, evidenced by radiographic findings such as minimal callus formation at the fracture site, mild decalcification, clear fracture lines, and an absence of osteosclerosis signs on X-rays. Otherwise, a fracture is considered normally healed [15]. In addition, this study conducted an internal validation of the prediction model using a 10-fold cross-validation method to ensure the stability and reliability of the model. Furthermore, 148 patients who met the same inclusion criteria were included in external validation. Based on their healing status four months post-surgery, these patients were similarly divided into a normal healing group (n=108) and delayed healing group (n=40).

Inclusion Criteria: 1. Patients diagnosed with open fractures of the extremities through imaging examinations and who underwent surgical treatment at Shanghai Sixth People's Hospital; 2. Patients aged 60 years or older; 3. Patients with complete clinical data; 4. Patients who had preoperative nutritional status assessments completed within one week before surgery; 5. Patients who did not receive any nutritional interventions prior to surgery. Exclusion Criteria: 1. Patients with closed fractures; 2. Patients with severe cardiac, hepatic, or renal dysfunction; 3. Patients with infectious diseases; 4. Patients with immunological diseases; 5. Patients who had previous surgeries on the same limb; 6. Patients who were pregnant or breastfeeding; 7. Patients with cognitive impairments or mental health disorders.

This study was approved by the Institutional Review Board (IRB) and Ethics Committee of Shanghai Sixth People's Hospital (2025-KY-235 (K)). Given the retrospective design of the study and the use of anonymized patient data, informed consent was waived.

Data extraction

Baseline demographics and clinical data were extracted through the case system, including BMI, fracture location, cause of fracture, fixation method, and intraoperative data. Nutritional status factors were assessed using validated scales such as MNA, NRS-2002, and SGA, with all measurements conducted under standardized conditions.

Gustilo Classification: The Gustilo classification is based on factors such as wound size, extent of soft tissue damage, and presence of vascular injury [16].

Type I: Wound less than 1 cm, typically a clean wound with no significant soft tissue damage or vascular injury; Type II: Wound greater than 1 cm but without extensive soft tissue damage, possibly involving minor to moderate muscle or skin loss; Type III: Further divided into three subtypes (A, B, C), involving extensive tissue damage and/or vascular injury; Type IIIA: Despite extensive soft tissue damage, the wound can be directly closed after debridement; Type IIIB: Flap grafting is needed to cover bone or tendon; Type IIIC: Accompanied by arterial injury requiring repair.

The American Society of Anesthesiologists (ASA) Physical Status Classification: ASA I: Healthy individuals with no systemic disease and good cardiopulmonary function; ASA II: Individuals with mild systemic disease and slight limitation in cardiopulmonary function, capable of performing general activities; ASA III: Individuals with mild to severe systemic disease, decompensated cardiopulmonary function, limited general activity, and discomfort; ASA IV: Individuals with severe systemic disease, poor cardiopulmonary function, and discomfort even at rest; ASA V: Moribund patients who are not expected to survive without the operation. Note: ASA IV indicates a moribund state. There were no patients with an ASA V grade in this study [17].

Outcome measures

The primary measurement in this study was the healing status of fractures at four months post-surgery, which was categorized into normal healing and delayed healing groups based on radiographic findings. The secondary indices included various nutritional status factors measured preoperatively within one day before surgery. These parameters comprised BMI, serum albumin, prealbumin, hemoglobin, lymphocyte count, MNA, NRS-2002, and SGA. All measures were conducted under standardized conditions to ensure accuracy and reliability.

Serological testing: Blood samples (4 ml) were collected from fasting patients one day prior to surgery. Serum was separated using serum separator tubes (SST, yellow-capped), and the samples were centrifuged at 1800 g for 10 minutes at a low temperature. The supernatant was extracted and stored in a -70°C freezer. Albumin and prealbumin levels were measured using an automatic biochemical analyzer (AU5800, Beckman Coulter). Additionally, serum total cholesterol (TC), high-density lipoprotein cholesterol (HDL-C), and low-density lipoprotein cholesterol (LDL-C) were also measured using the same automatic biochemical analyzer (AU5800, Beckman Coulter). For hemoglobin and lymphocyte count measurements, blood samples were collected in EDTA anticoagulant tubes (lavender-capped) and analyzed on a hematology analyzer (LH 750, Beckman Coulter).

Nutritional status scoring: All nutritional assessment scale results were completed by nurses under the guidance of a nutritionist from Shanghai Sixth People's Hospital one day prior to surgery.

(1) Mini Nutritional Assessment (MNA): The MNA is a tool specifically designed to assess the nutritional status of elderly individuals. It consists of four main sections, with a total score of 30 points: anthropometric measurements (up to 12 points), global assessment (up to 6 points), dietary habits (up to 6 points), and subjective assessment (up to 6 points) [18]. A total score ≥24 indicates good nutritional status; A score between 17 and 23.5 suggests a risk of malnutrition, requiring further observation and possible intervention; A score <17 indicates malnutrition, necessitating immediate action for nutritional support.

(2) Nutritional Risk Screening 2002 (NRS 2002): NRS 2002 is a standardized tool recommended by the European Society for Clinical Nutrition and Metabolism (ESPEN) to identify the risk of malnutrition in hospitalized patients. NRS 2002 consists of three main components: nutritional status score (0-3 points), severity of disease score (0-3 points), and an age adjustment score (adding 1 point for patients aged ≥70 years). The total score is the sum of these three components, with a maximum of 7 points. Based on the final score: A total score <3 indicates no nutritional risk and does not require special nutritional support; A total score ≥3 indicates a nutritional risk, suggesting further evaluation and consideration of nutritional support [19].

(3) Subjective Global Assessment (SGA): SGA is a clinical tool used to evaluate the overall nutritional status of patients based on medical history and physical examination. SGA classifies patients' nutritional status into three categories. Grade A (Well-nourished): Patients have stable weight, no significant weight loss, normal dietary intake, no apparent loss of appetite or difficulty eating, good muscle mass and subcutaneous fat, no obvious muscle wasting or fat loss; no edema or ascites; Grade B (Mild to moderate malnutrition): Patients have experienced 5-10% weight loss within the past six months, reduced dietary intake but still able to meet basic needs, some degree of muscle wasting or subcutaneous fat loss but not severe, possibly mild edema or ascites; Grade C (Severe malnutrition): Patients have lost more than 10% of their body weight within the past six months, significantly reduced dietary intake unable to meet basic nutritional needs, obvious muscle wasting and subcutaneous fat loss severely affecting physical function, evident edema or ascites, possibly accompanied by other complications [20].

Statistical analysis

Sample size was calculated based on a 37.1% delayed healing rate and 80% power to detect a 15% difference in nutritional markers (α=0.05). Using G*Power 3.1, a minimum of 190 patients was required, with 221 enrolled to account for potential dropouts. Data were processed using SPSS 29.0. Categorical data were expressed as percentages and frequencies and analyzed using the χ^2 test. All continuous data were tested for normality using the Shapiro-Wilk test; normally distributed data were presented as mean ± standard deviation (SD), and intergroup comparisons were performed using independent samples t-tests. Correlation analysis was conducted using Spearman analysis to assess the relationships between preoperative nutritional indicators and delayed fracture healing. Logistic regression analysis was used to identify nutritional status factors that influenced fracture healing. Based on the results of multivariate analysis, R Studio software was further utilized to construct a nomogram model to predict postoperative healing outcomes in elderly patients with open fractures of the extremities. Receiver operating characteristic (ROC) curves were constructed, and the area under the curve (AUC) was calculated to evaluate the predictive performance of the risk model for postoperative healing. An AUC value >0.9 indicates high predictive performance, an AUC between 0.71 and 0.90 indicates moderate predictive performance, and an AUC between 0.5 and 0.7 indicates poor predictive performance. A *P*-value <0.05 was considered significant.

Results

Demographic and basic data

A total of 221 elderly patients with open extremity fractures were included and divided into normal healing and delayed healing groups, yielding a delayed healing rate of 37.10% (**Table 1**). There were no significant differences between the two groups in gender, age, smoking history, alcohol use, comorbidities, fracture location, associated injuries, or time from injury to debridement. Similarly, there were no significant differences between groups regarding the cause of

Table 1. Comparison of demographic and basic data between the two groups

Variable	Normal healing group (n=139)	Delayed healing group (n=82)	t/x^2	p
Gender [n (%)]			0.001	0.977
Male	76 (54.68%)	45 (54.88%)		
Female	63 (45.32%)	37 (45.12%)		
Age (years)	68.26 ± 6.23	67.08 ± 6.21	1.361	0.175
BMI (kg/m²)	20.06 ± 1.34	19.58 ± 1.52	2.461	0.015
Smoking history [n (%)]	47 (33.81%)	31 (37.8%)	0.36	0.549
Alcohol consumption history [n (%)]	51 (36.69%)	27 (32.93%)	0.32	0.572
Comorbidities [n (%)]	58 (41.73%)	33 (40.24%)	0.047	0.829
Fracture location [n (%)]			0.013	0.909
Upper limb	74 (53.24%)	43 (52.44%)		
Lower limb	65 (46.76%)	39 (47.56%)		
Associated injuries [n (%)]	43 (30.94%)	27 (32.93%)	0.095	0.759
Time from injury to debridement (hours)	6.31 ± 1.42	6.35 ± 1.39	0.179	0.858
Cause of fracture [n (%)]			0.206	0.902
Traffic accident injury	90 (64.75%)	51 (62.20%)		
Fall injury	13 (9.35%)	9 (10.98%)		
Mechanical injury	36 (25.90%)	22 (26.83%)		
Gustilo classification [n (%)]			0.227	0.994
Type I	17 (12.23%)	10 (12.20%)		
Type II	56 (40.29%)	31 (37.80%)		
Type IIIA	39 (28.06%)	24 (29.27%)		
Type IIIB	18 (12.95%)	12 (14.63%)		
Type IIIC	9 (6.47%)	5 (6.10%)		
Fixation method [n (%)]			0.019	0.889
Internal fixation	81 (58.27%)	47 (57.32%)		
External fixation	58 (41.73%)	35 (42.68%)		
ASA physical status classification [n (%)]			2.277	0.131
Class I/II	109 (78.42%)	71 (86.59%)		
Class III/IV	30 (21.58%)	11 (13.41%)		

BMI: Body Mass Index; ASA: American Society of Anesthesiologists.

Table 2. Comparison of surgical situation between the two groups

Data	Normal healing group (n=139)	Delayed healing group (n=82)	t/x^2	p
Surgical duration (minutes)	184.28 ± 58.36	188.41 ± 57.62	0.51	0.611
Intraoperative blood loss (ml)	585.19 ± 179.56	582.67 ± 188.95	0.099	0.921
Intraoperative Complications [n (%)]	16 (11.51%)	13 (15.85%)	0.853	0.356
Length of hospital stay (days)	15.23 ± 2.14	14.72 ± 2.91	1.397	0.165

fracture, Gustilo classification, fixation method, or ASA classification. However, the normal healing group had a significantly higher mean BMI than the delayed healing group, suggesting that lower preoperative BMI may be associated with an increased risk of delayed fracture healing in elderly patients.

Surgical situation

There were no significant differences between the two groups in terms of surgical duration, intraoperative blood loss, incidence of intraoperative complications, or length of hospital stay (**Table 2**). This suggests that factors directly

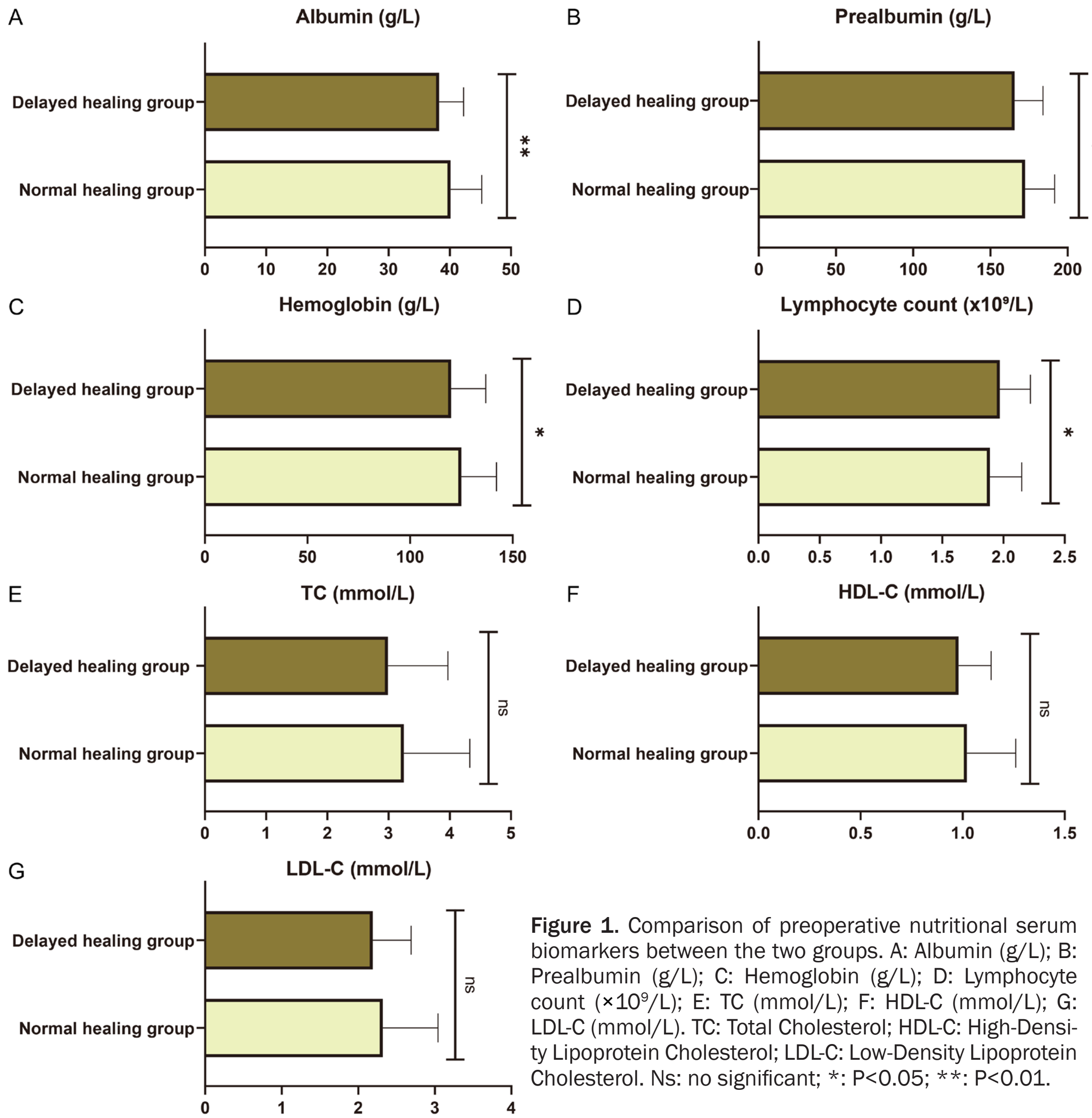


Figure 1. Comparison of preoperative nutritional serum biomarkers between the two groups. A: Albumin (g/L); B: Prealbumin (g/L); C: Hemoglobin (g/L); D: Lymphocyte count ($\times 10^9$/L); E: TC (mmol/L); F: HDL-C (mmol/L); G: LDL-C (mmol/L). TC: Total Cholesterol; HDL-C: High-Density Lipoprotein Cholesterol; LDL-C: Low-Density Lipoprotein Cholesterol. Ns: no significant; *: P<0.05; **: P<0.01.

related to the surgical procedures are not associated with postoperative wound healing outcome.

Serological testing

Analysis of preoperative nutritional serum biomarkers showed that the normal healing group had significantly higher levels of albumin, prealbumin, and hemoglobin compared to the delayed healing group (P<0.05 or P<0.01, **Figure 1**). In contrast, lymphocyte counts were significantly higher in the delayed healing group (P<0.05). No significant differences were observed in TC, HDL-C, or LDL-C between the two groups (P>0.05).

Nutritional status scoring

Assessment of preoperative nutritional status showed significant differences between the two groups (**Table 3**). The normal healing group had higher MNA scores and lower NRS 2002 scores compared to the delayed healing group, indicating better nutritional status and lower nutritional risk. According to the SGA, 77.7% of the normal healing group were well-nourished versus 64.63% in the delayed healing group, while mild to severe malnutrition was more common in the delayed healing group. These results suggest that poorer preoperative nutritional status is associated with delayed fracture healing in elderly patients.

Table 3. Comparison of preoperative nutritional status scale scores between the two groups

Data	Normal healing group (n=139)	Delayed healing group (n=82)	t/x^2	p
MNA scores	18.67 ± 5.32	17.04 ± 5.28	2.217	0.028
NRS 2002 scores	2.73 ± 0.51	3.04 ± 1.06	2.52	0.013
SGA classification [n (%)]			4.45	0.035
SGA-A	108 (77.7%)	53 (64.63%)		
SGA-B&C	31 (22.3%)	29 (35.37%)		

MNA: Mini Nutritional Assessment; NRS 2002: Nutritional Risk Screening 2002; SGA: Subjective Global Assessment.

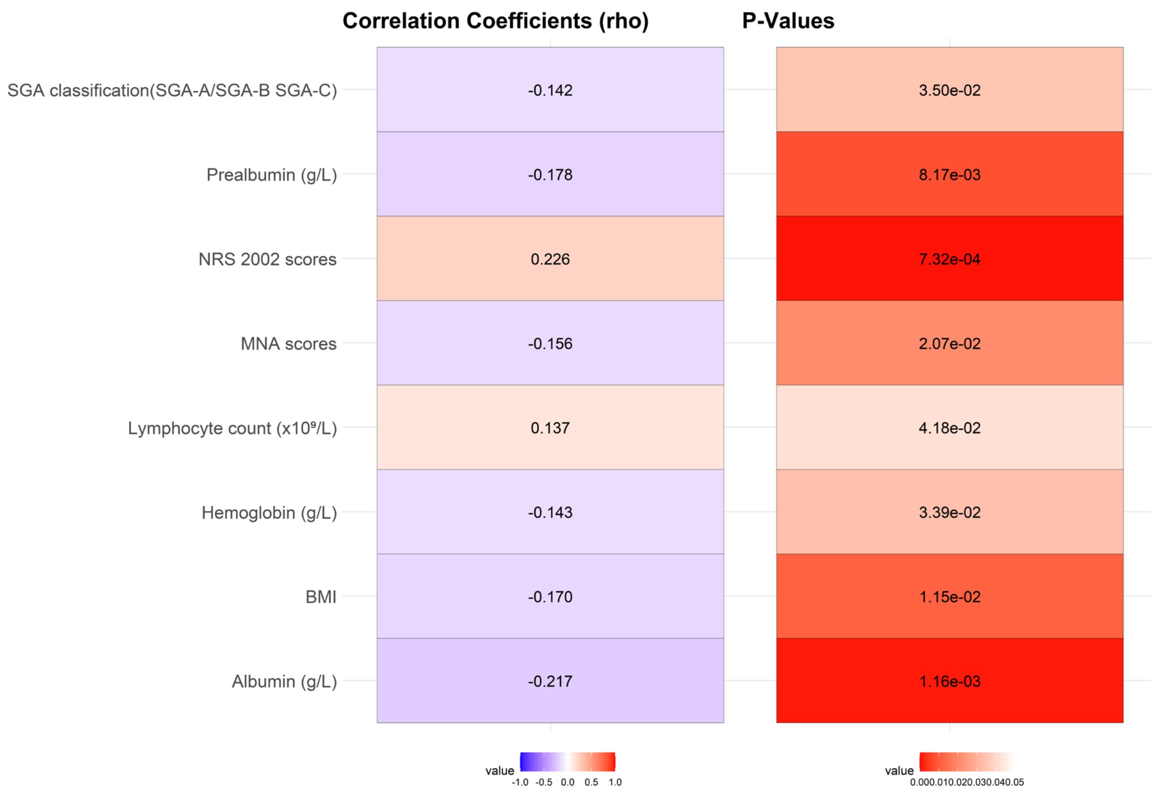


Figure 2. Correlation analysis between preoperative nutritional status indicators and postoperative delayed fracture healing. BMI: Body Mass Index; MNA: Mini Nutritional Assessment; NRS 2002: Nutritional Risk Screening 2002; SGA: Subjective Global Assessment.

Correlation analysis

Correlation analysis revealed significant associations between preoperative nutritional indicators and delayed fracture healing (**Figure 2**). Higher BMI (r=-0.170, P=0.011), albumin (r=-0.217, P=0.001), prealbumin (r=-0.178, P=0.008), hemoglobin (r=-0.143, P=0.034), MNA scores (r=-0.156, P=0.021), and better SGA classification (r=-0.142, P=0.035) were all negatively correlated with delayed healing, indicating that better nutritional status reduces risk. In contrast, higher lymphocyte count (r=0.137, P=0.042) and NRS 2002 scores (r=0.226, P<0.001) were positively correlated with delayed healing. These results highlight the importance of comprehensive preoperative nutritional assessment for predicting and potentially reducing delayed postoperative fracture healing in elderly patients.

Logistic regression analysis

Univariate and multivariate logistic regression analyses demonstrated that several preoperative nutritional indicators were significant predictors of delayed fracture healing in elderly patients (**Tables 4**, **5**). By univariate analysis, higher BMI, albumin, prealbumin, and hemoglobin were associated with lower odds of delayed

Table 4. Univariate logistic regression analysis of preoperative nutritional status indicators and postoperative delayed fracture healing

	Coefficient	Std. Error	Wald Stat	OR	OR CI Lower	OR CI Upper	P
BMI (kg/m^2)	-0.245	0.102	2.404	0.783	0.638	0.953	0.016
Albumin (g/L)	-0.085	0.031	2.764	0.919	0.864	0.974	0.006
Prealbumin (g/L)	-0.019	0.008	2.463	0.981	0.966	0.996	0.014
Hemoglobin (g/L)	-0.017	0.008	2.034	0.983	0.967	0.999	0.042
Lymphocyte count (×10^9/L)	1.246	0.550	2.266	3.478	1.201	10.455	0.023
MNA scores	-0.059	0.027	2.178	0.943	0.893	0.993	0.029
NRS 2002 scores	0.558	0.196	2.851	1.747	1.203	2.60	0.004
SGA classification (SGA-A:1/SGA-B, SGA-C:0) [n (%)]	-0.645	0.308	2.095	0.525	0.286	0.960	0.036

BMI: Body Mass Index; MNA: Mini Nutritional Assessment; NRS 2002: Nutritional Risk Screening 2002; SGA: Subjective Global Assessment.

Table 5. Multivariate logistic regression analysis of preoperative nutritional status indicators and postoperative delayed fracture healing

	Coefficient	Std. Error	Wald Stat	OR	OR CI Lower	OR CI Upper	P
BMI (kg/m^2)	-0.316	0.115	-2.737	0.729	0.581	0.914	0.006
Albumin (g/L)	-0.069	0.034	-2.049	0.933	0.873	0.997	0.040
Prealbumin (g/L)	-0.021	0.009	-2.435	0.979	0.963	0.996	0.015
Hemoglobin (g/L)	-0.016	0.009	-1.752	0.984	0.966	1.002	0.080
Lymphocyte count (×10^9/L)	1.469	0.644	2.282	4.346	1.230	15.354	0.023
MNA scores	-0.069	0.030	-2.325	0.933	0.880	0.989	0.020
NRS 2002 scores	0.507	0.209	2.426	1.661	1.102	2.502	0.015
SGA classification (SGA-A:1/SGA-B & C:0) [n (%)]	-0.737	0.346	-2.133	0.478	0.243	0.942	0.033

BMI: Body Mass Index; MNA: Mini Nutritional Assessment; NRS 2002: Nutritional Risk Screening 2002; SGA: Subjective Global Assessment.

healing, while higher lymphocyte count increased the odds. Nutritional assessments were also predictive: higher MNA scores and SGA classification indicated reduced risk, while higher NRS 2002 scores were associated with increased risk. In multivariate analysis, these associations remained significant. BMI, albumin, prealbumin, lymphocyte count, MNA, NRS 2002, and SGA were independent predictors. Hemoglobin showed a trend toward significance. These findings highlight the value of comprehensive preoperative nutritional assessment for predicting delayed fracture healing and guiding interventions to improve clinical outcomes in elderly patients.

ROC analysis

ROC analysis was applied to evaluate the predictive performance of preoperative nutritional indicators for delayed fracture healing in elderly patients (**Table 6** and **Figure 3**). BMI, albumin, prealbumin, and hemoglobin all showed moderate discriminatory ability. Albumin had the highest sensitivity but lower specificity. Lymphocyte count achieved the highest specificity but lower sensitivity. MNA scores demonstrated high specificity but low sensitivity, while NRS 2002 scores offered good specificity and balanced overall performance. A combined nomogram model further improved predictive accuracy, with an AUC of 0.964 (**Figures 4**, **5**).

External validation of the predictive model

In the external validation of the predictive model, no significant differences were observed in gender, age, smoking and alcohol history, comorbidities, fracture location, associated injuries, time to debridement, cause of fracture, Gustilo classification, fixation method, or ASA status between the normal and delayed healing groups. However, the delayed healing group showed a significantly lower BMI, albu-

Table 6. ROC analysis for preoperative nutritional indicators

	Best_ threshold	Sensitivities	Specificities	AUC	Youden_ index	F1_ score
BMI (kg/m^2)	19.97	0.646	0.547	0.601	0.193	0.31
Albumin (g/L)	40.865	0.805	0.475	0.63	0.28	0.195
Prealbumin (g/L)	174.705	0.732	0.482	0.606	0.214	0.257
Hemoglobin (g/L)	123.99	0.634	0.547	0.585	0.181	0.319
Lymphocyte count (×10^9/L)	1.975	0.524	0.662	0.582	0.186	0.5
MNA scores	14.195	0.354	0.835	0.593	0.189	0.422
NRS 2002 scores	3.08	0.524	0.799	0.635	0.323	0.562
SGA classification (SGA-A:1/SGA-B & C:0) [n (%)]	-Inf	1	0	0.435	0	0.541

BMI: Body Mass Index; MNA: Mini Nutritional Assessment; NRS 2002: Nutritional Risk Screening 2002; SGA: Subjective Global Assessment.

min, prealbumin, hemoglobin, and MNA scores, but higher lymphocyte count and NRS 2002 scores. Additionally, there was a greater proportion of malnutrition indicated by SGA classification in the delayed healing group. These results highlight that biochemical markers and nutritional status are more indicative of wound healing outcomes, suggesting their importance in predicting and managing delayed healing in trauma patients (**Table 7**). The ROC curve analysis in external validation cohorts, as depicted in **Figure 6**, demonstrates a high discriminatory ability of the predictive model with an AUC of 0.950, indicating excellent performance.

Discussion

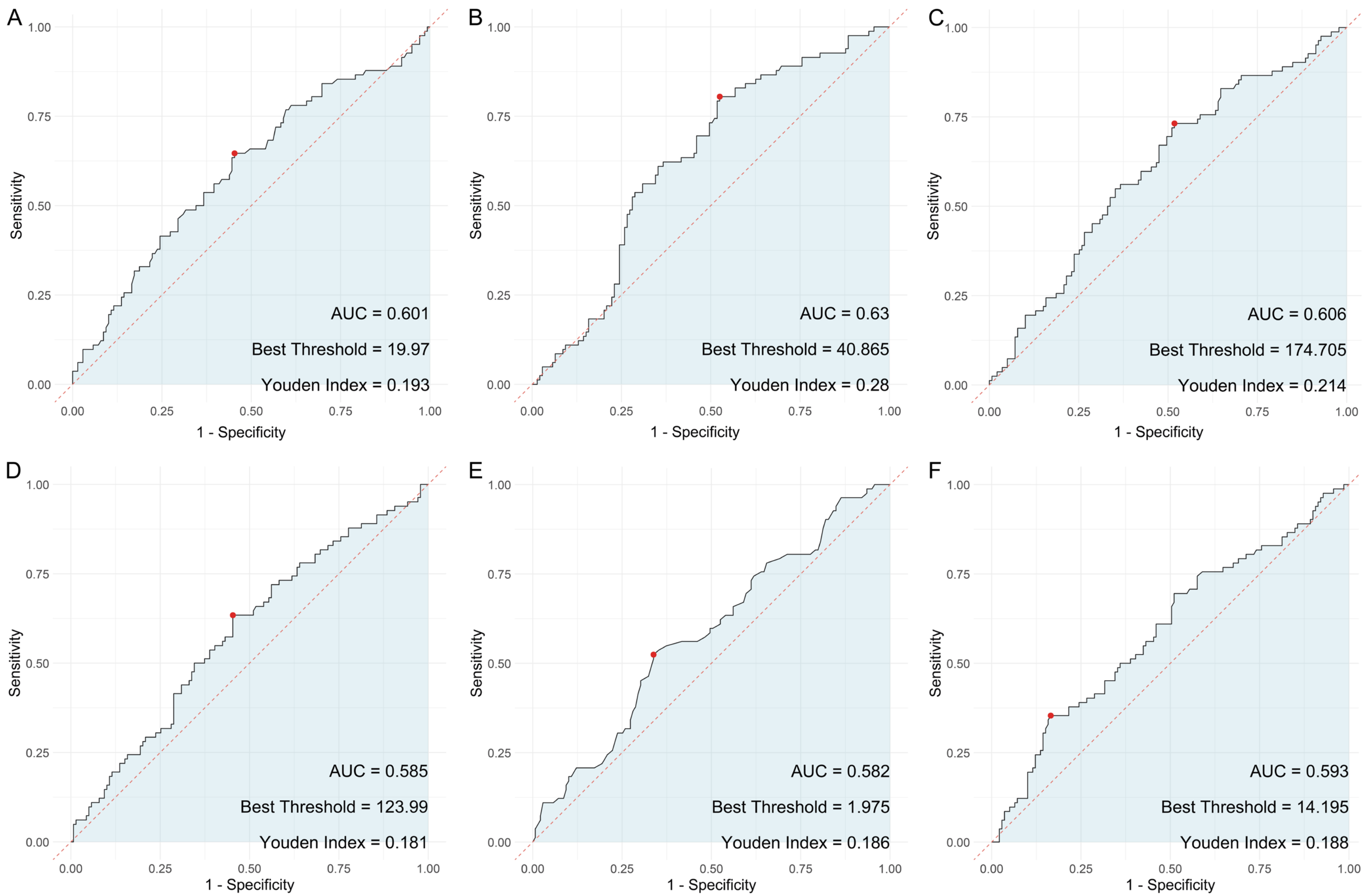
In this retrospective study, we investigated the predictive value of preoperative nutritional status parameters on delayed fracture healing in elderly patients who underwent surgery for open extremity fractures. We developed a nomogram model to assess individual risk and found that several nutritional indices were significant predictors of delayed healing.

Our findings align with previous studies highlighting the multifactorial nature of bone healing in the elderly [15]. Age-related changes in bone biology, such as reduced osteogenic capacity and impaired angiogenesis, create a less favorable environment for bone repair [21]. Additionally, aging is often accompanied by declining nutritional intake and metabolic function, leading to higher rates of protein-energy malnutrition and micronutrient deficiencies [22]. These deficiencies can disrupt the orchestrated cascade of bone healing, which requires coordinated cellular, molecular, and biomechanical events [23].

BMI emerged as a robust predictor of delayed healing, consistent with prior research indicating that adequate body mass and nutritional reserves are protective [24, 25]. Higher BMI levels may reflect better muscle and fat stores, serving as reservoirs of energy and substrates vital for tissue repair [26]. However, obesity and related metabolic syndromes could confound these findings, although our cohort predominantly consisted of individuals within a relatively narrow and lower BMI range, mitigating this concern.

Serum proteins, particularly albumin and prealbumin, were also strong predictors, reflecting both acute and chronic nutritional status [27]. Low albumin levels point to poor nutritional intake and ongoing systemic inflammation, both of which impair fracture healing [28]. Prealbumin, with its shorter half-life, is more sensitive to recent changes in nutritional status and catabolic stress [29]. Synthesizing these findings, we recognize that an adequate protein supply ensures the availability of amino acids critical for collagen synthesis, extracellular matrix production, and cellular proliferation within the fracture callus [30]. Deficits in protein intake delay the transition from the inflammatory to reparative phases, compromise matrix deposition, and reduce the mechanical integrity of new bone [30].

The association between hemoglobin and healing outcomes underscores the importance of oxygen-carrying capacity in fracture site metabolism [31]. Oxygen serves as a cofactor for post-translational modifications of collagen and as a substrate for cellular respiration during angiogenesis and tissue regeneration [32].


A
Sensitivity
1 - Specificity
AUC = 0.601
Best Threshold = 19.97
Youden Index = 0.193
B
AUC = 0.63
Best Threshold = 40.865
Youden Index = 0.28
C
AUC = 0.606
Best Threshold = 174.705
Youden Index = 0.214
D
AUC = 0.585
Best Threshold = 123.99
Youden Index = 0.181
E
AUC = 0.582
Best Threshold = 1.975
Youden Index = 0.186
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AUC = 0.593
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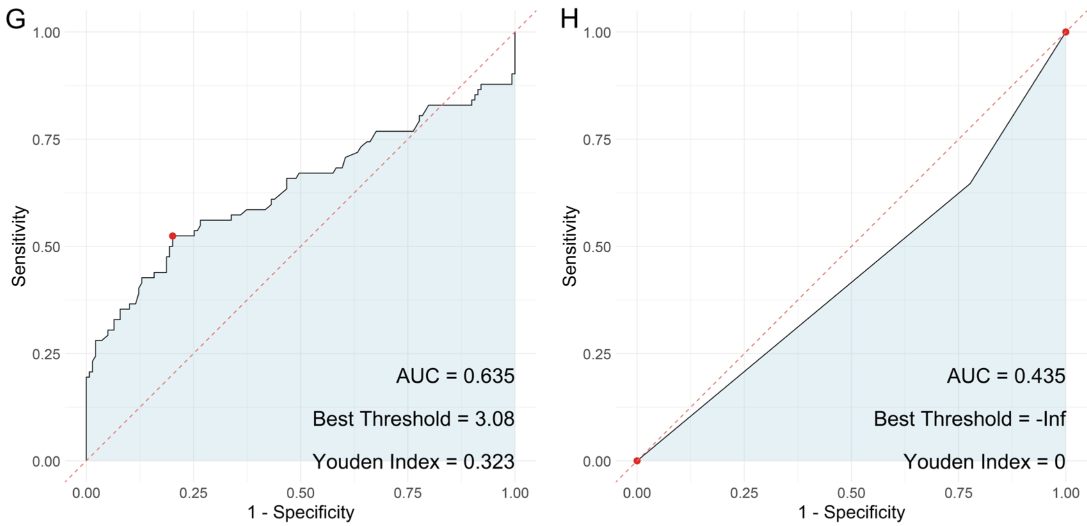

Figure 3. ROC curve analysis. A: BMI (kg/m^2); B: Albumin (g/L); C: Prealbumin (g/L); D: Hemoglobin (g/L); E: Lymphocyte count (×10^9/L); F: MNA scores; G: NRS 2002 scores; H: SGA classification. BMI: Body Mass Index; MNA: Mini Nutritional Assessment; NRS 2002: Nutritional Risk Screening 2002; SGA: Subjective Global Assessment; ROC: Receiver operating characteristic.

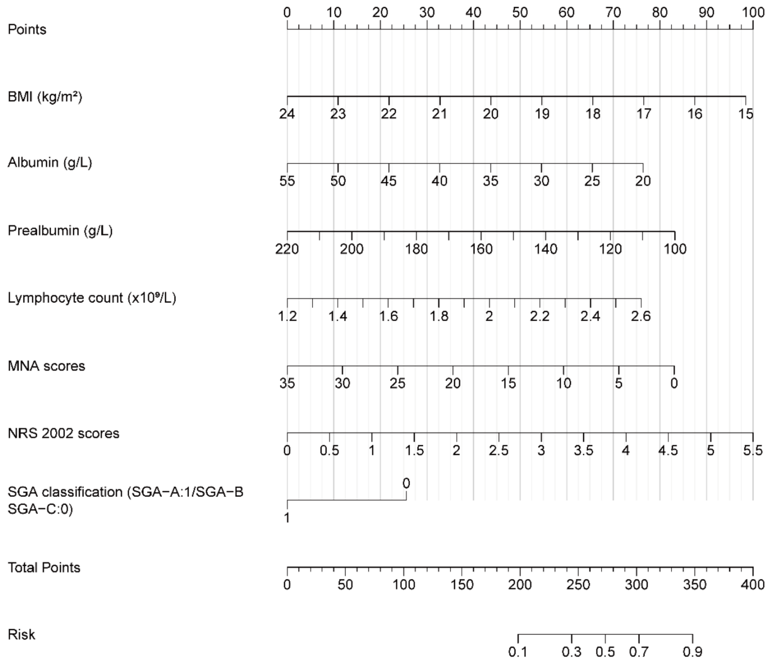

Figure 4. Nomogram model. BMI: Body Mass Index; MNA: Mini Nutritional Assessment; NRS 2002: Nutritional Risk Screening 2002; SGA: Subjective Global Assessment.

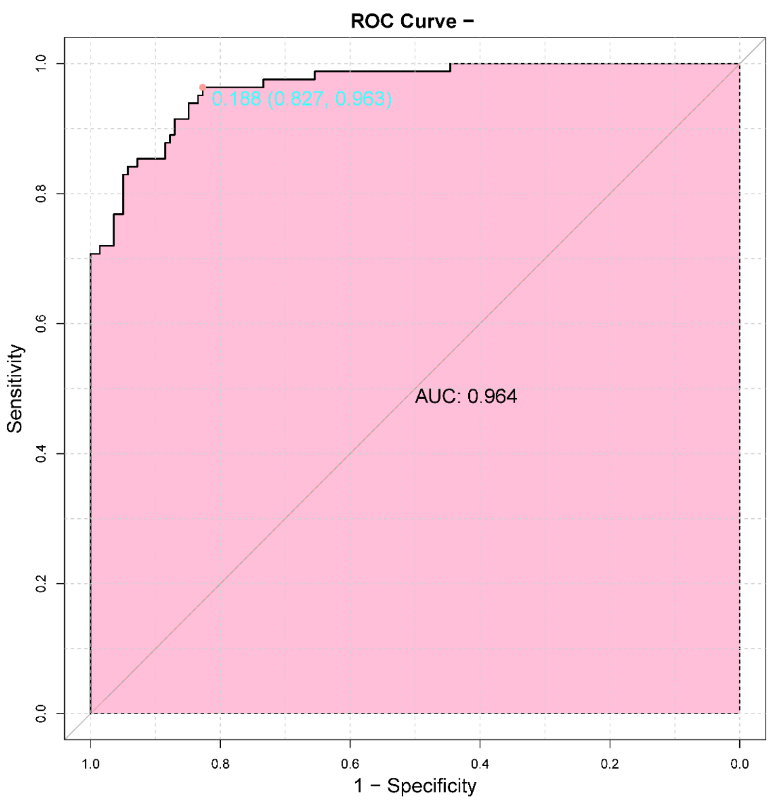

Figure 5. ROC curve analysis of nomogram model. ROC: Receiver operating characteristic.

Anemia, irrespective of etiology, leads to tissue hypoxia, stagnation of cellular processes, and impaired neovascularization, all detrimental for timely fracture resolution. In the elderly, anemia may arise from nutritional deficits (iron, folate, B12), chronic disease, or occult blood loss, creating a complex interplay between nutrition, systemic health, and local repair capacity [33].

The somewhat paradoxical finding of a higher lymphocyte count in the delayed healing group warrants nuanced interpretation [34]. In the context of trauma and healing, relative lymphocytosis may reflect ongoing inflammation or an immunological response to non-healing tissue [34]. Chronic systemic inflammation, often subclinical in elderly patients with comorbidities, can disrupt the regulated progression of bone healing, tipping the balance towards persistent catabolic signaling, matrix degradation, and ultimately delayed union [35]. It underscores the interconnectedness of immune and nutritional status in bone healing - a theme that continues to gain traction in the literature.

Standardized nutritional assessment tools, such as MNA, NRS 2002, and SGA, were independently linked to healing outcomes. These tools capture nuanced information about recent changes in weight, dietary intake, physical status, comorbidities, and disease severity, making them valuable in identifying covert or subclinical malnutrition [36]. These assessment methods prompt clinicians to recognize malnutrition risk early, even when overt laboratory de-

Table 7. External validation of the predictive model

Variable	Normal healing group (n=68)	Delayed healing group (n=40)	t/x^2	p
Gender [n (%)]			0.004	0.953
Male	37 (54.41%)	22 (55.00%)		
Female	31 (45.59%)	18 (45.00%)		
Age (years)	67.05 ± 6.14	68.21 ± 6.36	0.938	0.351
BMI (kg/m^2)	20.28 ± 1.51	19.61 ± 1.63	2.179	0.032
Smoking history [n (%)]	24 (35.29%)	15 (37.50%)	0.053	0.818
Alcohol consumption history [n (%)]	24 (35.29%)	13 (32.50%)	0.087	0.768
Comorbidities [n (%)]	29 (42.65%)	16 (40.24%)	0.073	0.788
Fracture location [n (%)]			0.037	0.847
Upper limb	37 (54.41%)	21 (52.50%)		
Lower limb	31 (45.59%)	19 (47.50%)		
Associated injuries [n (%)]	22 (32.35%)	14 (35.00%)	0.079	0.778
Time from injury to debridement (hours)	6.29 ± 1.35	6.33 ± 1.32	0.154	0.878
Cause of fracture [n (%)]			0.163	0.922
Traffic accident injury	43 (63.24%)	24 (60.00%)		
Fall injury	7 (10.29%)	5 (12.50%)		
Mechanical injury	18 (26.47%)	11 (27.50%)		
Gustilo classification [n (%)]			0.379	0.984
Type I	9 (13.24%)	5 (12.50%)		
Type II	27 (39.71%)	15 (37.50%)		
Type IIIA	20 (29.41%)	11 (27.50%)		
Type IIIB	8 (11.76%)	6 (15.00%)		
Type IIIC	4 (5.88%)	3 (7.50%)		
Fixation method [n (%)]			0.057	0.812
Internal fixation	39 (57.35%)	22 (55.00%)		
External fixation	29 (42.65%)	18 (45.00%)		
ASA physical status classification [n (%)]			0.521	0.470
Class I/II	54 (79.41%)	34 (85.00%)		
Class III/IV	14 (20.59%)	6 (13.41%)		
Albumin (g/L)	40.09 ± 5.14	37.62 ± 4.13	2.583	0.011
Prealbumin (g/L)	173.02 ± 19.33	164.69 ± 18.45	2.197	0.030
Hemoglobin (g/L)	127.35 ± 17.45	120.11 ± 16.88	2.108	0.037
Lymphocyte count (×10^9/L)	1.85 ± 0.31	1.99 ± 0.35	2.210	0.029
MNA scores	19.32 ± 5.41	17.13 ± 5.36	2.047	0.043
NRS 2002 scores	2.72 ± 0.55	3.12 ± 1.11	2.129	0.038
SGA classification [n (%)]			4.149	0.042
SGA-A	56 (82.35%)	26 (65.00%)		
SGA-B & C	14 (20.59%)	14 (35.00%)		

BMI: Body Mass Index; ASA: American Society of Anesthesiologists; MNA: Mini Nutritional Assessment; NRS 2002: Nutritional Risk Screening 2002; SGA: Subjective Global Assessment.

rangements are absent, ensuring timely intervention and risk stratification in the perioperative period.

The construction of a nomogram model integrating these nutritional factors demonstrated high discriminative power, outperforming individual parameters through their collective contributions. This approach reflects an evolving paradigm in perioperative care, where risk stratification is increasingly multidimensional.

Latent mechanisms bridging malnutrition and poor bone healing are multifaceted [36]. First,

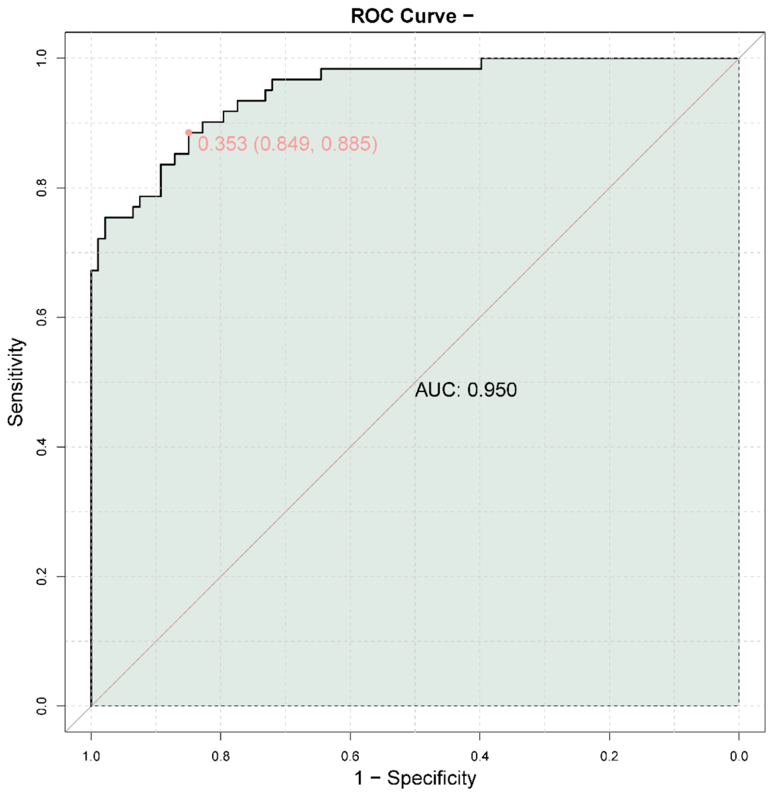

Figure 6. ROC curve analysis in external validation cohort.

systemic malnutrition impairs cellular proliferation and differentiation, including mesenchymal stem cells and osteoprogenitors crucial for callus formation [36]. Protein and caloric deficits limit the synthesis of growth factors (e.g., IGF-1), matrix components (type I collagen), and enzymes required for mineralization [37]. Vitamin and micronutrient deficiencies (vitamin D, calcium, magnesium, zinc) further impede proper bone metabolism and immune regulation at the fracture site [37]. Malnourished patients often have diminished antioxidant capacity and impaired inflammatory resolution, extending the duration of catabolic phase and reducing the efficiency of reparative processes [38].

Moreover, poor nutritional status is linked to decreased wound healing capacity, higher infection rates, and increased susceptibility to secondary complications (e.g., pressure ulcers, pneumonia), all of which can secondarily impair rehabilitation and delay fracture union [39]. Malnutrition exerts systemic effects, including muscle wasting and sarcopenia, which reduce mobility and mechanical loading required to stimulate bone regeneration through mechanotransduction [39]. Ultimately, a vicious cycle ensues: poor nutrition leads to delayed healing, which prolongs immobility and hospitalization, further limiting nutritional intake and compounding sarcopenia.

Another important consideration is immunosenescence in the elderly, which compounds the effects of malnutrition. Inadequate protein and micronutrient availability can weaken innate and adaptive immune responses, predisposing to infection and inadequate regulation of inflammation at the fracture site [40]. Conversely, chronic low-grade inflammation (inflammaging) can drive persistent tissue breakdown and hinder the reparative switch necessary for successful healing [29].

Despite the promising results, our study has several limitations. The retrospective design and single-center cohort limit generalizability and introduce potential biases. Future prospective multicenter studies are needed to validate the nomogram model and confirm its clinical utility. Additionally, while we controlled for known confounders, unmeasured variables may still influence the observed associations. The reliance on serological markers and standardized assessments may overlook subtle variations in nutritional status not captured by these measures.

While our retrospective design and single-center cohort impose certain limitations, the findings advocate strongly for routine, comprehensive nutritional evaluation of elderly patients with open long bone fractures. Interventions may include early nutritional supplementation, optimization of protein and micronutrient intake, and targeted management of anemia and inflammatory conditions. The integration of a nomogram model into clinical practice could facilitate preoperative counseling, guide individualized perioperative interventions, and serve as a framework for further validation in prospective multicenter studies.

In conclusion, preoperative nutritional status exerts profound influence on bone healing after open extremity fractures in elderly patients, mediated by intricate biological, metabolic, and immunological pathways. Systematic assessment and optimization of nutritional indices should be embedded in the standard of care for this population, with risk prediction models serving as practical tools for personalized, evidence-based management. These measures hold promise for mitigating the risk of delayed healing, reducing healthcare burden, and improving functional recovery among the growing elderly fracture population.

Disclosure of conflict of interest

None.

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