

ORIGINAL RESEARCH ARTICLE

The relationship between functional prognosis in patients with infection after upper limb trauma: a predictive model based on HbA1c stratification and the mediating role of delayed rehabilitation

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ABSTRACT

Objective: To investigate the association between preoperative glycated hemoglobin (HbA1c) and upper limb function (Disabilities of the Arm, Shoulder and Hand [DASH] score) at 6 months post-surgery in patients with fracture-related infection (FRI) after upper limb trauma, and to test the mediating role of rehabilitation initiation time.

Methods: This retrospective cohort study included 100 patients with FRIs after upper limb trauma surgery (September 2020 to August 2025). Demographic characteristics, fracture features, HbA1c levels, time to initiate rehabilitation, and debridement frequency of patients were collected. With the DASH score at 6 months after surgery as the outcome variable, multiple linear regression was used to analyze the association between HbA1c and functional prognosis, and the Bootstrap method was used to test the mediating effect of rehabilitation initiation time.

Results: HbA1c was significantly positively correlated with the DASH score ($\beta = 6.90$, 95% CI 3.91–9.89, $p < 0.001$). Recovery initiation time played a partial mediating role between the HbA1c and the DASH scores, with a mediating ratio of 27% (indirect effect 2.04, 95% CI 0.63–3.59, $p = 0.004$). There was no significant interaction between HbA1c and recovery initiation time or debridement frequency ($p > 0.05$). Thresholding effect analysis did not find a definite breakpoint (log-likelihood ratio test $p = 0.220$), and HbA1c was linearly related to the DASH score.

Conclusion: Preoperative HbA1c is independently associated with 6-month upper limb function in patients with post-traumatic infection, with rehabilitation initiation time playing a partial mediating role. Clinicians should prioritize glycemic control and initiate rehabilitation as early as safely possible.

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Introduction

Upper limb fractures have significant epidemiological implications in clinical practice, especially in cases of forearm and elbow fractures. Upper limb fractures are common injuries in orthopedic trauma. Although most upper limb fractures have a good prognosis through surgical treatment, the occurrence of fracture-related infection (FRI) after surgery remains a serious clinical challenge [1]. FRI can lead to delayed bone healing, failed internal fixation, joint stiffness, and multiple surgeries, which seriously affect the recovery of upper limb function in patients [2]. In addition, there is a significantly increased risk of multiple surgeries after infection, especially in patients over 45 years old with purulent drainage and incomplete bone healing at the time of infection [3]. Therefore, identifying the key factors that affect the functional prognosis of FRI patients is of great significance for optimizing treatment strategies and improving patient outcomes.

Glycated hemoglobin (HbA1c) is a reliable indicator reflecting the average blood glucose level in the recent 2–3 months and is widely

used to assess the risk of perioperative complications in patients with diabetes. Previous studies have confirmed that elevated HbA1c is closely associated with infections and poor wound healing after elective orthopedic surgery [4, 5]. In addition, elevated blood glucose under traumatic stress may also affect postoperative complications, and stress-induced hyperglycemia in nondiabetic trauma patients is also associated with a poor prognosis. A prospective study showed that stress hyperglycemia significantly increased the risk of postoperative adverse events (OR = 4.43, 95% CI: 2.11–9.30) and prolonged hospital stays, regardless of whether diabetes was present or not [6]. This suggests that the clinical significance of post-traumatic hyperglycemia is not limited to diabetic patients; stress-induced hyperglycemia in nondiabetic individuals is also an important risk factor for postoperative complications. However, the predictive value of HbA1c for postoperative infection in patients with orthopedic trauma remains controversial: a retrospective study found no significant association between HbA1c levels and postoperative

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surgical site infection in patients with acute fractures, and routine monitoring failed to effectively warn of infection risk [7]. This suggests that the mechanism by which HbA1c affects the prognosis of trauma patients is more complex, and its role in functional outcomes in the FRI population remains unclear.

Recovery initiation time is considered a key modulatable factor influencing functional recovery after fracture surgery. Early rehabilitation intervention can effectively prevent joint stiffness and muscle atrophy [8]. But for FRI patients, the infection itself often leads to a forced delay in the rehabilitation process. Repeated debridement, antibiotic treatment, and pain control often make early functional exercise difficult to implement [9]. Theoretically, hyperglycemia may affect functional prognosis in two ways: either directly impure the quality of tissue healing or indirectly delay the initiation of recovery [10]. However, there is a lack of direct evidence-based evidence as to whether HbA1c affects the recovery of upper limb function in FRI patients by delaying the time of recovery initiation.

At present, studies at home and abroad have mostly focused on the etiological characteristics, surgical treatment strategies, and infection control effects of FRI, while relatively less attention has been paid to the trajectory of functional recovery after infection control. Although studies have explored the impact of factors such as age and comorbidities on the treatment outcome of FRI, the interaction mechanism between HbA1c and recovery initiation time in functional prognosis has not been fully explored. This study aims to analyze the role of these factors in functional recovery in patients with upper limb FRI, with the expectation of providing a reference for clinical intervention. A retrospective cohort study design was used to explore the association between preoperative HbA1c levels and upper limb function (Disabilities of the Arm, Shoulder and Hand [DASH] score) at 6 months after surgery and to examine the mediating role of rehabilitation initiation time, to provide evidence-based evidence for perioperative blood glucose management and early rehabilitation intervention in patients with FRI.

Methods

This study used a retrospective cohort design and consecutively enrolled patients who developed FRIs after upper limb trauma surgery in the orthopedics department of Ningbo No. 6 Hospital from September 2020 to August 2025.

Inclusion criteria

(1) Age ≥ 18 years, gender not limited; (2) Fresh fractures, injury to surgery time ≤ 3 weeks, with open reduction and internal fixation treatment; (3) Preoperative HbA1c test results are available; if not

tested before surgery, the test value within 48 hours of admission is used; (4) Meets the diagnostic criteria for infection related to fractures; (5) Postoperative follow-up time ≥ 6 months; (6) Complete clinical data such as surgical records, microbiological tests, and imaging reports.

Exclusion criteria

(1) Pathological fractures; (2) Active infection before the operation; (3) In a state of severe immunosuppression such as after organ transplantation, during chemotherapy, or long-term high-dose hormone use; (4) Combined with severe cognitive impairment or mental illness, unable to cooperate to complete follow-up; (5) Loss to follow-up or absence of DASH score records at 6 months after surgery. The patient screening process is shown in Figure 1. This study followed the ethical principles of the Declaration of Helsinki.

Baseline data

The baseline data collected in this study covered multi-dimensional clinical information, including demographic characteristics such as age, gender, body mass index (BMI), smoking history, and American Society of Anesthesiologists (ASA) classification, all of which were derived from medical records; fracture features such as fracture site, open fracture Gustilo classification, and injury mechanism were taken from surgical records; glycemic-related variables included diabetic status (present/absent), from medical records; preoperative test values of HbA1c divide HbA1c into three levels: Level 1 (<6.5%, normal), level 2 (6.5–8.0%, well controlled), and level 3 (>8.0%, poorly controlled). Perioperative-related variables include operation duration (minutes) and open fracture status (yes/no).

Outcome measures and follow-up methods

We record the number of debridements and the initiation time of rehabilitation. Recovery time is defined as the number of weeks in which the patient is first explicitly recorded in the medical record after surgery or the last infection-related debridement that ‘allows and instructs the patient to begin nonresistive joint movement of the affected upper limb (including passive movement, active assisted movement, or active movement)’.

Primary outcome measure

The primary outcome measure was the Upper Limb Disability Assessment Scale (DASH) score at 6 months after surgery. The score

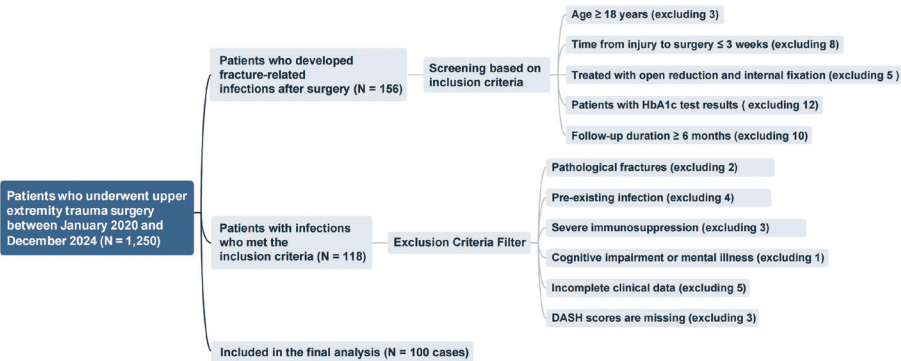


Figure 1. Flowchart of patient screening.

was assessed by trained specialist nurses through telephone interviews as part of the department's routine clinical follow-up process and recorded in the electronic medical record system. The researchers extracted DASH score data from all included patients by reviewing the medical record system. All cases completed at least 6-month follow-up (± 2 weeks) after the operation.

Statistics and analysis

All statistical analyses were performed using SPSS 26.0 and R language 4.1.0, with the test level set at $\alpha = 0.05$. In comparison of baseline characteristics, the independent sample *t*-test (expressed as $\bar{x} \pm s$) was used for continuous variables with normal distribution, and the Mann-Whitney U test [expressed as median (interquartile range)] was used for nonnormal distribution; the chi-square test or Fisher's exact test (in cases (%)) was used for categorical variables, and the baseline characteristics of the three groups were further compared based on HbA1c stratification (<6.5%, 6.5–8.0%, >8.0%). For the missing data, cases were directly excluded when the HbA1c deficiency rate was less than 5%; for missing rates between 5 and 20%, multiple imputation (5 repeats) was performed using the chain equation method.

Univariate analysis and collinearity diagnosis

With the DASH score at 6 months after surgery as the dependent variable, univariate linear regression analysis was performed on all candidate independent variables. For continuous variables included in the multi-factor model, collinearity diagnosis was performed, and a variance inflation factor (VIF) > 5 was considered severe multicollinearity.

Multivariate regression analysis

We construct a multiple linear regression model based on clinical importance and the results of univariate analysis. The main analysis used HbA1c as a continuous variable to establish the main effect model (Model 1) and the model with interaction terms (Model 2, including HbA1c $\times$ rehabilitation initiation time, HbA1c $\times$ debridement ≥ 2 times). The Bootstrap resampling method (1000 times) was used to calculate the optimity-corrected R^2 , and a calibration curve was plotted to evaluate model stability.

Sensitivity analysis

HbA1c was converted into three categorical variables (< 6.5%, 6.5–8.0%, and >8.0%), and models with interaction terms were established on the basis of adjusting for the same covariates to verify the robustness of the results.

Mediating effect analysis

The Bootstrap method (repeated sampling 1000 times) was used to test the mediating effect of rehabilitation initiation time between the HbA1c and the DASH scores. With HbA1c as the independent variable (*X*), rehabilitation initiation time as the mediating variable (*M*), and the DASH score as the dependent variable (*Y*), the number of open fractures and debridement was controlled. The criterion for significant mediating effect is that the 95% confidence interval of the indirect effect does not include 0, and the mediating ratio is calculated (indirect effect/total effect $\times 100\%$). The analysis was performed using the Hayes PROCESS macro or the R language mediation package.

Results

Population baseline characteristics and blood glucose stratification

A total of 100 patients with postoperative upper limb infections were included and divided into three groups based on preoperative HbA1c levels: Group 1 (< 6.5%, $n = 48$), Group 2 (6.5–8.0%, $n = 32$), and Group 3 (> 8.0%, $n = 20$). As shown in Table 1, with the increase of HbA1c levels, the age, BMI, operation duration, and recovery initiation time of the patients all increased (all $p < 0.05$). All patients in Group 3 had a history of diabetes (100%), which was significantly higher than the other two groups ($p < 0.001$). There was a significant difference in DASH scores at 6 months after surgery among the three groups ($p < 0.001$), and the higher the HbA1c, the worse the functional prognosis. The remaining indicators such as gender, smoking history, ASA classification, fracture site, injury mechanism, and debridement frequency were evenly distributed among the three groups (all $p > 0.05$).

Results of univariate linear regression analysis

Univariate linear regression analysis showed that BMI ($p = 0.041$), open fracture ($p = 0.028$), history of diabetes ($p < 0.001$), recovery

Table 1. Comparison of patient characteristics (stratified by HbA1c).

Characteristic	Group 1 <i>N</i> = 48	Group 2 <i>N</i> = 32	Group 3 <i>N</i> = 20	<i>p</i>
Age, Median (Q1, Q3)	51 (45, 61)	56 (50, 62)	62 (55, 70)	0.003
Male, <i>n</i> (%)	30 (62.5%)	19 (59.4%)	13 (65.0%)	0.916
BMI, kg/m ² , Median (Q1, Q3)	25.7 (24.1, 27.7)	26.6 (25.4, 30.7)	29.7 (27.3, 32.1)	< 0.001
Smoking, <i>n</i> (%)	18 (37.5%)	12 (37.5%)	9 (45.0%)	0.828
ASA classification III–IV, <i>n</i> (%)	7 (14.6%)	9 (28.1%)	8 (40.0%)	0.071
Proximal humeral fracture, <i>n</i> (%)	32 (66.7%)	26 (81.3%)	15 (75.0%)	0.346
Open fracture, <i>n</i> (%)	5 (10.4%)	5 (15.6%)	6 (30.0%)	0.141
High-energy injury, <i>n</i> (%)	16 (33.3%)	7 (21.9%)	6 (30.0%)	0.539
History of diabetes, <i>n</i> (%)	3 (6.3%)	26 (81.3%)	20 (100.0%)	< 0.001
Duration of surgery, Median (Q1, Q3)	103 (80, 122)	111 (87, 124)	130 (109, 141)	0.012
Debridement times, <i>n</i> (%)	6 (12.5%)	8 (25.0%)	7 (35.0%)	0.091
Recovery initiation time, Median (Q1, Q3)	2.60 (1.80, 3.30)	3.90 (2.80, 5.65)	5.30 (3.55, 6.10)	< 0.001
DASH, Median (Q1, Q3)	25 (18, 34)	37 (21, 40)	46 (35, 59)	< 0.001
HbA1c, Median (Q1, Q3)	5.69 (5.48, 6.03)	7.17 (6.90, 7.53)	9.14 (8.54, 9.51)	< 0.001

Note: Group 1: HbA1c < 6.5%; Group 2: HbA1c 6.5–8.0%; Group 3: HbA1c > 8.0%. The Kruskal-Wallis rank sum test was used for comparisons between groups of continuous variables, and the chi-square test or Fisher's exact probability method was used for comparisons between groups of categorical variables. BMI: body mass index; ASA: American Society of Anesthesiologists; HbA1c: hemoglobin; DASH: Disabilities of the Arm, Shoulder and Hand.

Table 2. Univariate linear regression analysis of factors associated with the DASH score.

Characteristic	N	Beta	95% CI	p
Age (years)	100	0.21	-0.07, 0.49	0.145
Gender (male)	62	-1.06	-7.54, 5.41	0.748
BMI (kg/m ²)	100	0.85	0.05, 1.65	0.041
Smoking (yes)	39	-4.75	-11.12, 1.63	0.148
ASA classification (III–IV)	24	4.13	-3.19, 11.44	0.272
Proximal humeral fractures (yes)	73	1.18	-5.90, 8.25	0.745
Open fractures (yes)	16	9.50	1.13, 17.86	0.028
High-energy damage (yes)	29	-3.10	-10.00, 3.80	0.380
History of diabetes (yes)	49	13.00	7.26, 18.73	< 0.001
HbA1c (%)	100	7.48	5.68, 9.29	< 0.001
Duration of the operation (minutes)	100	0.08	-0.02, 0.18	0.126
Debridement times (≥ 2 times)	21	2.53	-5.17, 10.23	0.521
Recovery start time (weeks)	100	4.97	3.50, 6.43	< 0.001

Note: Data are presented as regression coefficient β , 95% confidence interval (CI), and p -values. BMI: body mass index; ASA: American Society of Anesthesiologists; HbA1c: hemoglobin; DASH: Disabilities of the Arm, Shoulder and Hand.

initiation time ($p < 0.001$), and HbA1c level ($\beta = 7.48$, $p < 0.001$) were significantly associated with the DASH score (Table 2). Among them, history of diabetes, open fractures, higher HbA1c, longer recovery initiation time, and higher BMI were all positively correlated with higher DASH scores (i.e. poorer upper limb function). The remaining factors such as age, gender, smoking, ASA classification, proximal humeral fracture, high-energy injury, operation duration, and debridement ≥ 2 times were not statistically associated with the DASH score at 6 months after surgery (all $p > 0.05$).

Results of multivariate linear regression analysis

Before the multivariate regression analysis, a collinearity diagnosis was made for all continuous variables, suggesting no serious multicollinearity problem (Supplementary Table 1).

The DASH score at 6 months after surgery was used as the dependent variable, and age, BMI, open fracture, recovery initiation time, debridement frequency, history of diabetes, and HbA1c were included to construct a multiple linear regression model. The main analysis included HbA1c as a continuous variable (Table 3, model 1), and the results showed that the model was overall significant (adjusted $R^2 = 0.439$, $p < 0.001$). HbA1c ($p < 0.001$) and recovery initiation time ($p = 0.002$) were significantly positively correlated with the DASH score, while the remaining covariates were not statistically significant (all $p > 0.05$). Model 2 further included the interaction

items between HbA1c and rehabilitation initiation time, and between HbA1c and debridement times ≥ 2 times, both of which were not significant (all $p > 0.05$), suggesting no effect modification.

Sensitivity analysis was conducted using the three categorical variables of HbA1c (Supplementary Table 2), and after adjusting for the same covariates, Model 3 showed that the DASH score was significantly higher in the $> 8.0\%$ group compared with the HbA1c $< 6.5\%$ group ($p = 0.033$), while there was no significant difference in the $6.5\text{--}8.0\%$ group ($p = 0.159$); recovery initiation time remained significantly correlated ($p = 0.003$). Model 4 and Model 5, respectively, examined the interaction between HbA1c groups and rehabilitation initiation time, debridement frequency, and all interaction terms were not statistically significant ($p > 0.05$), suggesting no effect modification.

The mediating effect of rehabilitation initiation time between HbA1c and DASH

Table 4 and Figure 2 show that the total effect of HbA1c on the DASH score is significant ($p < 0.001$). After the introduction of recovery initiation time, the indirect effect was significant ($p = 0.004$), and the direct effect was significant ($p < 0.001$). The mediating proportion was 27.0% (95% CI 8.9–45.9%), indicating that approximately 27% of the effect of HbA1c on functional prognosis was achieved through delayed recovery initiation time. The results remained robust after adjusting for age, BMI, and open fractures.

Dose-response relationship and threshold effect analysis of HbA1c versus the DASH score

We explore the dose-response relationship between HbA1c and the DASH score after adjusting for age, BMI, and open fractures (Figure 3A). The overall association test showed a significant correlation between HbA1c and the DASH score (p for overall = 0.034); the nonlinear test did not reach statistical significance (p for nonlinear = 0.251), suggesting that the relationship between the two was basically in line with the linear model.

A piecewise linear regression model was further used for threshold effect analysis (Table 5, Figure 3B). Standard linear regression showed that for every 1% increase in HbA1c, the DASH score increased by 7.54 points (95% CI 5.47–9.62, $p < 0.001$). Piecewise regression based on this breakpoint showed that when HbA1c $< 9.125\%$, the slope $\beta = 6.26$ ($p < 0.001$); when HbA1c $\geq 9.125\%$, the slope increased to $\beta = 19.47$ ($p = 0.030$). But, the log-likelihood ratio test showed no

Table 3. Multivariate linear regression analysis of factors associated with the DASH score.

Variables	Model 1 (main effect)		Model 2 (with interaction terms)	
	β (95% CI)	p	β (95% CI)	p
Main effects				
Age (years)	-0.02 (-0.24, 0.20)	0.869	-0.02 (-0.24, 0.20)	0.863
BMI (kg/m ²)	0.03 (-0.65, 0.71)	0.926	0.04 (-0.64, 0.73)	0.899
Open fracture (yes)	2.60 (-4.11, 9.30)	0.450	2.67 (-4.10, 9.44)	0.442
Recovery initiation time (weeks)	2.73 (1.03, 4.44)	0.002	0.75 (-7.12, 8.63)	0.852
Debridement times (≥ 2 times)	-4.28 (-10.31, 1.76)	0.168	-8.78 (-40.09, 22.53)	0.584
History of diabetes (yes)	-5.29 (-12.46, 1.87)	0.151	-4.46 (-12.10, 3.18)	0.256
HbA1c (%)	6.90 (3.91, 9.89)	< 0.001	5.28 (-0.64, 11.19)	0.084
Interaction items				
Debridement times $\times$ HbA1c	-	-	0.62 (-3.59, 4.83)	0.775
Recovery initiation time $\times$ HbA1c	-	-	0.28 (-0.79, 1.35)	0.609
Model fitting metrics				
R^2	0.479	-	0.481	-
Adjust R^2	0.439	-	0.429	-

Note: Data are expressed as regression coefficient β , 95% confidence interval (CI), and p value. Categorical variables were referenced by a specific category (open fractures were referenced by closed fractures, and history of diabetes was referenced by no history of diabetes). BMI: body mass index; HbA1c: hemoglobin; DASH: Disabilities of the Arm, Shoulder and Hand.

Table 4. Analysis of the mediating effect of recovery initiation time in the association between HbA1c and the DASH score.

Effect type	Coefficient (95% CI)	p
Total effect	7.54 (5.56, 9.58)	< 0.001
Indirect effect	2.04 (0.63, 3.59)	0.004
Direct effect	5.51 (3.73, 7.64)	< 0.001
Proportion mediated	27.0% (8.9%, 45.9%)	-

Note: The independent variable was HbA1c, the mediating variable was the time to start rehabilitation, and the dependent variable was the DASH score 6 months after surgery; The data were expressed as regression coefficients and 95% CI, and the mediating proportion was the percentage of the indirect effect to the total effect. The CI was estimated using the bootstrap method (1000 repeated samples), and the model adjusted for age, BMI, and open fractures. BMI: body mass index; HbA1c: hemoglobin; CI: confidence interval; DASH: Disabilities of the Arm, Shoulder and Hand.

significant difference in goodness-of-fit between the piecewise model and the linear model ($p = 0.220$). These results suggest that although the relationship between HbA1c and the DASH score shows an increasing slope after $>9.125\%$, it can still be regarded as a continuous linear association overall.

Sensitivity analysis: Generalized Additive Model validation

Generalized Additive Model (GAM) further verified the nonlinear possibility of HbA1c and the DASH score. As shown in [supplementary Table 3](#), the edf for the smoothing terms (HbA1c) was 1.00, indicating a strict linear relationship ($p < 0.001$), which corroborates the restricted cubic spline (RCS) and threshold analysis results. Model-adjusted $R^2 = 0.385$ suggested that HbA1c combined with covariates could account for 38.5% of the functional prognostic variation.

Discussion

This study examined the association between preoperative HbA1c levels and upper limb function (DASH score) at 6 months after surgery in patients with infection after upper limb trauma and examined the mediating role of recovery initiation time. The results showed a significant positive correlation between HbA1c and the DASH score; that is, the higher the blood glucose level, the worse the prognosis of upper limb function. Recovery initiation time plays a partial

mediating role, with about 27% of the HbA1c effect achieved through delayed recovery initiation.

After controlling for age, BMI, open fractures, debridement frequency, and history of diabetes, HbA1c remained significantly associated with DASH scores. This result is largely consistent with previous studies on the prognosis of orthopedic surgery. One review reported that chronic poor glycemic control (marked by elevated HbA1c levels) was associated with adverse outcomes such as infection, impaired wound healing, and poor functional recovery after joint replacement [11]. Some scholars also reported that progressive elevation of HbA1c levels was associated with a significantly increased risk of limb adverse events in patients with peripheral artery disease who underwent lower extremity revascularization [12]; Diabetic foot patients with poor blood glucose control also had significantly delayed recovery of walking function after surgery [13]. This study further extended this association to the population with upper limb trauma infection, providing new evidence for the study of glucose management and functional prognosis in different orthopedic subgroups.

The mechanisms by which hyperglycemia affects functional prognosis may include the following aspects. First, hyperglycemia can directly reduce proteoglycan (PG) levels in tendons, interfere with glycosaminoglycan synthesis and sulfation processes, and, at the same time, lead to reduced collagen synthesis and abnormal crosslinking, thereby affecting the structural integrity and healing quality of soft tissues such as tendons and ligaments [14]. Second, under hyperglycemic conditions, muscle protein catabolism is enhanced, which is not conducive to muscle strength recovery and functional reconstruction. In addition, advanced glycation end products (AGEs) deposit in tendons, joint capsules, and ligaments; reduce collagen molecule sliding through lateral molecular interconnections; inhibit the discrete plastic injury mechanism of tendons; significantly reduce tissue extensibility and strain energy capacity; and ultimately increase the risk of joint stiffness and mechanical injury [15, 16]. Diabetes also impairs the proliferation, apoptosis, and remodeling ability of tendon cells, further disrupting tendon homeostasis and healing processes [17]. These factors working together may result in poor recovery of upper limb function even when the infection is controlled.

It should be noted that among the 49 diabetic patients included in this study, all patients in the HbA1c $> 8.0\%$ group had a history of diabetes. Diabetic patients often have other metabolic disorders, vascular lesions, and systemic complications, which may independently affect functional prognosis [18, 19]. Although we corrected for history of diabetes in the multivariate regression, there may still be unmeasured residual confounding (such as the duration of diabetes, insulin-dependent status, other comorbidities, etc.). Therefore, the association between HbA1c and functional prognosis may partly reflect the combined effect of diabetes-related comorbidities rather than the direct impact of blood glucose levels alone.

The mediating effect analysis showed that recovery initiation time played a partial mediating role between HbA1c and the DASH score, with a mediating ratio of 27%. This result reveals an indirect pathway by which HbA1c affects functional prognosis: patients with hyperglycemia tend to have delayed recovery initiation, which, in turn, leads to poorer functional outcomes.

The reasons for delayed recovery initiation can be multifaceted. In clinical practice, doctors may tend to postpone rehabilitation training due to concerns about poor wound healing in patients with high blood sugar. At the same time, postoperative pain and swelling may be more pronounced in both post-traumatic stress hyperglycemia and diabetic patients [20, 21]. As a result, patients' willingness and the ability to be active on their own decline. Joint

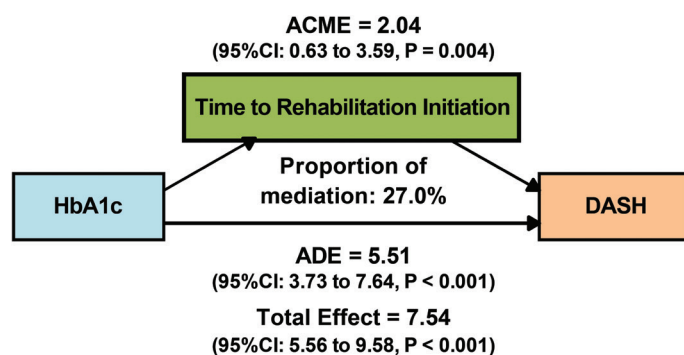


Figure 2. Path diagram of the mediating effect of recovery initiation time between HbA1c and the DASH score. The mediating effect roadmap shows the mechanism by which HbA1c affects the DASH score 6 months after surgery through the time of rehabilitation initiation. The values in the graph represent standardized regression coefficients (β). Corrected for open fracture status and debridement times (≥ 2). HbA1c: hemoglobin; DASH: Disabilities of the Arm, Shoulder and Hand.

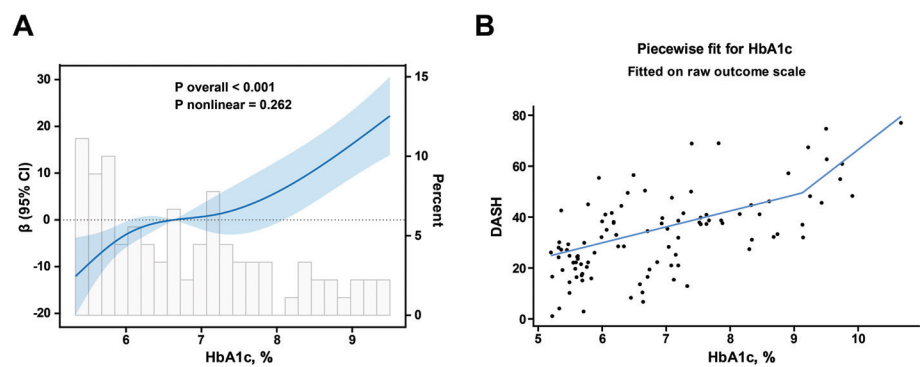


Figure 3. Dose–response relationship between HbA1c and the DASH score and threshold effect analysis. (A) Dose–response relationship between HbA1c fitted by the restricted cubic spline (RCS) regression model and the DASH score at 6 months after surgery. The solid line represents the fitting curve, and the shaded area represents the 95% confidence interval. The model corrected for age, BMI, and open fracture status. (B) The HbA1c threshold effect identified by the piecewise linear regression model. The vertical dotted line indicates the best breakpoint position (HbA1c = 9.125%), and the two solid lines are the fitting lines for HbA1c < 9.125% and ≥ 9.125%. After adjusting for age, BMI, and open fracture. BMI: body mass index; HbA1c: hemoglobin; DASH: Disabilities of the Arm, Shoulder and Hand.

stiffness and muscle atrophy resulting from delayed rehabilitation initiation, regardless of the cause, are associated with poor functional prognosis. The findings suggest that for infected patients with poor glycemic control, even if the infection itself is under control, functional recovery will still be significantly affected if rehabilitation initiation is not timely.

Further analysis revealed no significant interaction between HbA1c and the recovery initiation time was found in this study. This result suggests that the effect of HbA1c on functional prognosis does not depend on the timing of rehabilitation initiation. In other words, hyperglycemia itself remains an independent risk factor for functional recovery even in patients with an earlier recovery initiation time. This echoes the conclusion from previous studies that elevated HbA1c is associated with an increased risk of postoperative infection and prolonged hospital stay [22]. The two findings are not contradictory: the time of recovery initiation as a mediating pathway explains ‘how’ HbA1c affects prognosis, while the lack of significant interaction indicates that the harm of HbA1c is persistent, and that blood glucose management should be emphasized regardless of the time of recovery initiation.

In addition, the thresholding effect analysis showed no clear breakpoint effect between HbA1c and the DASH score. Although the regression coefficient increased significantly when HbA1c > 9.125%, the log-likelihood ratio test suggested no significant difference in goodness-of-fit between the piecewise linear model and the standard linear model. Combined with the nonlinear test ($p = 0.251$) in the RCS

analysis and the effective degrees of freedom of 1.00 in the GAM model, this study supports that the relationship between HbA1c and the DASH score can be regarded as linear overall. This finding is consistent with previous orthopedic surgical studies, showing a continuous positive correlation between HbA1c and postoperative adverse outcomes, suggesting that the impact of HbA1c on functional prognosis may be continuously increasing rather than having a definite safety threshold [23].

This study has the following limitations, and in response to these limitations, subsequent studies can take corresponding improvement measures: First, the single-center retrospective design may lead to selection bias and information bias. Future multi-center, prospective cohort studies can be conducted with strict inclusion and exclusion criteria and standardized data collection procedures to reduce bias. Second, the sample size is relatively limited, especially with only 20 cases in the HbA1c > 8.0% group, which may affect the statistical power of subgroup analysis and interaction tests. The wider confidence interval after HbA1c > 9.125% in the threshold analysis is also related to the smaller sample size. The sample size can be expanded later, increasing the number of cases in subgroups with high HbA1c levels (>8.0%, >9.125%) to enhance statistical power. Third, the definition of rehabilitation initiation time depends on medical records, and there may be differences among different doctors in terms of the scale of ‘permitted activity’. Although this study used a uniform operational definition to reduce information bias to some extent, a standardized rehabilitation initiation assessment process could be developed in the future, with a dedicated person responsible for recording, to further reduce information bias [24]. Fourth, factors such as rehabilitation compliance and the intensity of the rehabilitation program were not included, which may have an impact on functional prognosis. Subsequent studies could specifically collect detailed rehabilitation-related information and incorporate it into the regression model for a more comprehensive analysis of the influencing factors [25]. Fifth, the follow-up period was only 6 months, and the functional prognosis in the longer term (such as 1 year, 2 years) was unclear. The follow-up period could be extended to 1 year to explore the long-term effect of HbA1c on the functional prognosis of the upper limb.

Conclusion

In patients with infection after upper limb trauma surgery, preoperative HbA1c levels were independently associated with upper

Table 5. Threshold effect analysis of the relationship between HbA1c and the DASH score.

Model	Adjusted β (95% CI)	p
Fitting by standard Linear regression model	7.54 (May 47, September 62)	< 0.001
Fitting by piecewise Linear regression model (Break-Point = 9.125)		
HbA1c < 9.125	6.26 (3.30, 9.22)	< 0.001
HbA1c ≥ 9.125	19.47 (1.96, 36.97)	0.030
Log likelihood ratio		0.220

Note: All models were adjusted for age, BMI, and open fracture status. Breakpoints were determined by iterative search and selected based on the principle of model goodness of fit maximization. Log-likelihood ratio tests are used to compare the goodness-of-fit differences between piecewise linear models and standard linear models. BMI: body mass index; HbA1c: hemoglobin; CI: confidence interval; DASH: Disabilities of the Arm, Shoulder and Hand.

limb function 6 months after surgery. For every 1% increase in HbA1c, the DASH score increases by an average of 6.90 points. Recovery initiation time plays a partial mediating role, with about 27% of the effect achieved through delayed recovery initiation. The effect of HbA1c on functional prognosis does not change with the timing of rehabilitation initiation or the number of debridements. In clinical practice, emphasis should be placed on blood glucose management in patients with hyperglycemia, and rehabilitation training should be initiated as early as possible under the premise of ensuring safety to improve the functional prognosis of the upper limbs.

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Competing interests

The authors have no conflicts of interest to declare.

Availability of data and materials

The data that support the findings of this study are not publicly available due to privacy reasons but are available from the corresponding author upon reasonable request.

Ethics approval

The present study was approved by the Ethics Committee of Ningbo No. 6 Hospital (No. 2026-23(L)). All procedures were performed in accordance with the ethical standards of the Institutional Review Board and The Declaration of Helsinki and its later amendments or comparable ethical standards.

Informed consent

This study was a retrospective analysis and did not require an informed consent.

Artificial intelligence (AI) statement

This article does not use the artificial intelligence (AI) generator to generate text.

Authors' contributions

Sheng Chen and YiFei Zhu: Conceptualization, Data curation, Formal Analysis, Methodology, Validation, Visualization, Writing-original draft.

MinTao Tian: Data curation, Formal Analysis, Investigation, Validation.

HongLei Hu and Lu Xu: Investigation, Soft-ware, Validation.

BiYun Li: Project administration, Funding acquisition, Supervision, Writing-review and editing.

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