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*Original Article*

# Efficacy of microsurgical vascular and nerve repair combined with free venous grafting for avulsed amputated fingers

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**Abstract:** Objective: To evaluate the clinical efficacy of microsurgical vascular and nerve repair combined with free venous grafting (FVG) for avulsed amputated fingers, and to identify the relevant prognostic factors. Methods: A retrospective analysis was conducted on 186 patients with avulsed amputated fingers who received microsurgical repair combined with FVG at Yulin First Hospital from January 2020 to December 2023. All patients completed a 12-month standardized postoperative follow-up. Outcomes included finger survival rate, Visual Analogue Scale (VAS) score, 36-Item Short Form Health Survey (SF-36) score, Michigan Hand Questionnaire (MHQ) score, static two-point discrimination (2PD), and postoperative complication incidence. LASSO regression with 10-fold cross-validation was used to screen predictive variables, followed by multivariate logistic regression analysis. The area under the curve (AUC) and decision curve analysis were applied to evaluate the predictive performance and clinical application value of the model. Results: The overall finger survival rate was 94.09% (175/186), and the postoperative complication rate was 35.5% (66/186). At 6 months after surgery, patients showed significantly reduced VAS scores, along with significantly improved SF-36 scores, MHQ scores, and 2PD (all $P < 0.001$). The cumulative hand function recovery rate at 12 months postoperatively was 84.95% (158/186). LASSO regression screened six valid predictive variables: age, injury-to-operation time, avulsion type, injured finger type, multiple finger injury, and vascular injury length. The constructed prediction model exhibited excellent discrimination (AUC = 0.913). Conclusion: Microsurgical vascular and nerve repair combined with FVG can achieve a high survival rate and significant functional improvement in patients with avulsed amputated fingers. The validated prognostic prediction model supports individualized clinical treatment and stratified rehabilitation intervention for such patients.

**Keywords:** Avulsed amputated fingers, vascular and nerve repair, free venous grafting, finger replantation, prognostic factors

## Introduction

Hand trauma is highly prevalent in emergency and outpatient trauma settings. Finger amputation, a common severe hand injury, has long attracted clinical attention due to its high disability rate and substantial impacts on patients' daily life and work [1]. With the continuous development of industrialization and mechanization, high-energy hand trauma has become increasingly complex, making avulsed amputated fingers more frequent in clinical practice.

Different from clean incised finger amputations, avulsed amputations are mainly caused by mechanical crushing, violent traction or rotational shear force. These injuries are usually accompanied by extensive avulsion of skin and soft tissues, long-segment contusion of blood vessels and nerves, and tendon avulsion, which bring great difficulties to finger replantation surgery [2-4].

Vascular repair is the core and most challenging step in the replantation of avulsed amputated fingers. The intimal damage of injured blood vessels is often far more extensive than macroscopic observation. Direct end-to-end vascular anastomosis usually causes excessive anastomotic tension and easily induces postoperative

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thrombosis due to unremoved damaged intima [5, 6]. Although modern microsurgical techniques have greatly improved the success rate of finger replantation, direct anastomosis is often unfeasible for the vascular defects commonly observed in avulsed amputations [7].

Free venous grafting (FVG) has become a key complementary technique for such cases. Harvesting superficial veins from the forearm or foot dorsum to bridge vascular defects can effectively eliminate anastomotic tension and provide intact, healthy vascular intima for blood vessel reconstruction [8, 9]. However, the clinical application value of FVG in avulsed finger replantation remains controversial. Some scholars argue that FVG prolongs operation time and increases surgical trauma, and high-quality clinical evidence supporting its long-term functional benefits is still insufficient.

Most previous studies adopted finger survival rate as the sole or primary evaluation endpoint, which is overly one-sided. Clinically, many patients achieve successful finger survival after replantation but suffer from long-term postoperative pain, sensory disturbance and joint stiffness, resulting in unsatisfactory quality of life and hand function [10, 11]. In recent years, pain quantification and overall health status evaluation have been gradually applied in hand trauma research, but their comprehensive application in the efficacy evaluation of avulsed amputated finger repair is still limited.

Although FVG is not an innovative surgical technique, this study has three distinct innovations. First, we established a patient-centered multidimensional efficacy evaluation system covering finger survival, pain degree, quality of life, hand function, sensory recovery and postoperative complications. Second, we screened prognostic variables via LASSO regression and constructed and validated a prognostic prediction model for hand function recovery using ROC curve and decision curve analysis (DCA). Third, we formulated a severity grading system for finger avulsion injuries and corresponding tiered diagnosis and treatment strategies.

Based on the above research background, this study retrospectively analyzed the clinical data of patients with avulsed amputated fingers treated with microsurgical neurovascular repair combined with FVG. The findings aim to provide evidence-based references for clinical treatment decision-making and prognostic assessment of this injury type.

## Materials and methods

### *Study design*

This study was a single-center retrospective cohort study. Patients were diagnosed with avulsed amputated fingers who received surgical treatment at Yan'an Hospital of Traditional Chinese Medicine from January 2020 to December 2023. All patients underwent microsurgical vascular and nerve repair combined with FVG and completed a standardized 12-month postoperative follow-up. Core functional and symptomatic evaluations were performed at 6 months after surgery. This study was approved by the Ethics Committee of Yan'an Hospital of Traditional Chinese Medicine. The requirement for written informed consent was waived due to the retrospective nature of the study.

### *Inclusion and exclusion criteria*

Inclusion criteria: (1) Age ranged from 18 to 70 years; (2) Clinical diagnosis of avulsed amputated finger caused by mechanical crushing, violent traction or rotational force with confirmed soft tissue avulsion injury; (3) Received microsurgical vascular and nerve repair combined with FVG; (4) Complete preoperative baseline and injury-related clinical data; (5) Completed 12-month standardized postoperative follow-up with intact follow-up data.

Exclusion criteria: (1) Patients with severe uncontrolled systemic diseases (cardiovascular diseases, coagulation disorders, severe diabetes) that could not tolerate surgery; (2) Patients with combined severe multiple injuries or hemorrhagic shock requiring priority management of life-threatening injuries; (3) Patients with pre-existing severe dysfunction or deformity of the affected finger; (4) Heavy smokers (more than 10 cigarettes daily) who failed to quit smoking during the perioperative period; (5) Patients with confirmed alcohol dependence syndrome; (6) Patients with poorly controlled hypertension (systolic blood pressure > 160 mmHg or diastolic blood pressure > 100 mmHg); (7) Patients with peripheral vascular disease, including diabetic vasculopathy with

glycated hemoglobin (HbA1c) > 8%; (8) Patients with pre-existing peripheral neuropathy of the affected limb caused by any etiology.

*Sample size calculation*

Sample size calculation was performed using PASS 16.0 software based on the Cox proportional hazards regression model formula. The statistical parameters were set as follows: two-tailed α = 0.05, statistical power (1-β) = 0.80, expected hazard ratio of the primary risk factor = 2.0, endpoint event rate = 15%, and coefficient of determination \(R^2\) = 0.30. The minimum required sample size was calculated as 162 cases. A total of 186 eligible patients were enrolled in this study, which met the sample size requirement.

*Surgical methods*

All operations were performed by a fixed team of certified microsurgeons. All patients received brachial plexus block or general anesthesia, and a tourniquet was applied to the affected limb before surgery.

(1) Debridement and intraoperative exploration: Thorough debridement was performed under a surgical microscope (10-25 × magnification) to remove devitalized tissues and contaminants. The injury range of blood vessels and nerves were fully explored. Given the common long-segment intimal contusion in avulsed vascular injuries, damaged vascular segments were trimmed until smooth and hematoma-free intima was observed under the microscope, and the actual length of vascular defects was measured and recorded.

(2) Bone and tendon reconstruction: Fracture ends were fixed with Kirschner wires or mini titanium plates to restore finger skeletal integrity. Flexor and extensor tendons were repaired sequentially to reconstruct finger motor function. Tendon grafting or tendon transfer was performed for cases with severe tendon avulsion and defect.

(3) Vascular repair with FVG: Direct end-to-end vascular anastomosis was attempted first. For cases with unavoidable vascular defects or excessive anastomotic tension, FVG was performed to bridge the defective segments. Superficial veins matching the diameter of the recipient vessels were harvested from the volar forearm or dorsal foot. The harvested veins were reversed before transplantation to avoid venous valve-induced blood flow obstruction. The graft vein length was slightly longer than the actual vascular defect to eliminate anastomotic tension. The arterial and venous graft ratio was adjusted according to intraoperative conditions, and one digital artery and two dorsal digital veins were routinely reconstructed.

(4) Nerve repair: Under microscopic visualization, digital nerve epineurial repair was performed using 9-0 or 10-0 atraumatic sutures to restore finger sensory function. Nerve grafting or nerve transfer was adopted for patients with nerve defects.

(5) Wound coverage: Primary suture was used for simple wound closure. Local flaps, free flaps or skin grafting were applied to cover large skin and soft tissue defects. After surgery, all patients received routine anticoagulation, antispasmodic and anti-infective treatment. Fingertip vascular status was continuously monitored to detect and manage vascular crises in a timely manner.

*Outcome measures*

Primary outcomes: Finger survival rate (the proportion of replanted fingers surviving without secondary amputation within 12 months postoperatively) and cumulative hand function recovery rate (the proportion of patients who met the preset hand function recovery criteria at 12 months postoperatively).

Secondary outcomes: (1) Pain severity: assessed via VAS (0 points = no pain, 10 points = extreme pain) before surgery and at 6 months postoperatively [12]. (2) Quality of life: evaluated using SF-36 (8 dimensions; higher total scores indicate better overall health status) before surgery and at 6 months postoperatively [13]. (3) Overall hand function: measured by MHQ (6 dimensions including hand function, daily activity, work ability, pain, appearance and satisfaction; higher scores indicate better hand function) before surgery and at 6 months postoperatively [14]. (4) Static sensory function: static 2PD of the finger pulp was detected; lower values indicate higher sensory sensitivity [15]. (5) Postoperative complications: including vascular crisis (arterial spasm or thrombosis), incision infection, poor wound healing, and persistent finger swelling lasting more than 7 days.

**Table 1.** Baseline demographic and injury characteristics

| General Characteristics | n (%) |
|---|---|
| Gender | |
| Male | 142 (76.34) |
| Female | 44 (23.66) |
| Age (years) | 39.83±10.30 |
| Time from injury to surgery | |
| ≤ 6 h | 127 (68.28) |
| > 6 h | 59 (31.72) |
| Avulsion type | |
| Complete | 78 (41.94) |
| Incomplete | 108 (58.06) |
| Cause of injury | |
| Traction | 86 (46.24) |
| Crush | 64 (34.41) |
| Mechanical incision | 36 (19.35) |
| Injured finger type | |
| Thumb | 49 (26.34) |
| Other fingers | 137 (73.66) |
| Multiple finger injury | |
| Yes | 41 (22.04) |
| No | 145 (77.96) |
| Vascular injury length | |
| ≤ 3 cm | 117 (62.90) |
| > 3 cm | 69 (37.10) |
| Infection status | |
| Yes | 16 (8.60) |
| No | 170 (91.40) |
| Skin and soft tissue defect | |
| Yes | 57 (30.65) |
| No | 129 (69.35) |

The total complication rate was calculated accordingly.

*Statistical methods*

SPSS 26.0 and R 4.2.0 software were used for data analysis. Measurement data were expressed as mean ± standard deviation. Independent samples t-test was used for intergroup comparison of measurement data. Pearson correlation analysis was performed to analyze the correlations between MHQ scores and SF-36 scores, VAS scores total active motion (TAM) and 2PD values.

LASSO logistic regression with 10-fold cross-validation was used to screen potential prognostic variables for hand function recovery. Two penalty parameters (lambda.min and lambda.1se) were determined. To avoid model overfitting caused by limited sample size, lambda.1se ($\lambda = 0.023$) was selected to construct the final prediction model. Univariate logistic regression was performed on all candidate variables to calculate odds ratios (ORs) and 95% confidence intervals (CIs).

Cumulative incidence function (CIF) was used for competing risk analysis. ROC curve, Hosmer-Lemeshow test, Brier score and decision curve analysis (DCA) were adopted to evaluate the discrimination, calibration and clinical net benefit of the model. A two-tailed $P$ value < 0.05 was defined as statistically significant.

## Results

*Baseline demographic and injury characteristics*

A total of 186 patients were enrolled, including 142 males and 44 females, with a mean age of 39.83±10.30 years (range, 18-67 years). The injury-to-operation time ranged from 2 to 12 hours, including 127 patients (68.28%) with surgery within 6 hours and 59 patients (31.72%) with surgery more than 6 hours after injury.

In terms of injury type, 78 cases (41.94%) were complete avulsed amputations and 108 cases (58.06%) were incomplete avulsed amputations. The main injury causes were traction injury (46.24%), crush injury (34.41%) and mechanical incision injury (19.35%). The injured fingers included thumbs (26.34%) and other fingers (73.66%); 41 patients (22.04%) had multiple finger injuries. Vascular injury length was ≤ 3 cm in 117 cases (62.90%) and > 3 cm in 69 cases (37.10%). The postoperative incision infection rate was 8.60%, and 30.65% of patients had combined skin and soft tissue defects. Detailed baseline data are shown in **Table 1**.

*Finger survival and postoperative complications*

Of the 186 replanted fingers, 175 survived successfully, yielding an overall survival rate of 94.09%, while 11 fingers developed necrosis (5.91%). A total of 66 patients developed postoperative complications, with a total complication rate of 35.5%. Persistent postoperative finger swelling was the most common complication, followed by vascular crisis, poor wound

**Table 2.** Finger survival and postoperative complications

| Indicator | n (%) |
|---|---|
| Survival status of replanted finger | |
| Survival | 175 (94.09) |
| Necrosis | 11 (5.91) |
| Postoperative complications | |
| Vascular crisis | 19 (10.22) |
| Persistent swelling of replanted finger > 7 days | 28 (15.05) |
| Incision infection | 8 (4.30) |
| Poor wound healing | 12 (6.45) |
| Total complications | 66 (35.48) |

healing and incision infection. All complications were effectively controlled after symptomatic treatment, and no severe adverse outcomes occurred (**Table 2**).

*Detailed management and prognosis of complications*

The targeted treatment, prognosis and preventive measures for each type of postoperative complication are summarized in **Table 3**.

*Functional and pain indicators before and after surgery*

Preoperative baseline indicators were as follows: VAS score 7.77±1.05, SF-36 score 53.58±8.57, MHQ score 49.74±9.17, and 2PD value 10.95±2.35. At 6 months postoperatively, patients achieved significant pain relief with a reduced VAS score of 1.94±0.66. Meanwhile, quality of life and hand function were markedly improved: SF-36 score increased to 78.88±7.98 and MHQ score increased to 82.55±6.29. The 2PD value decreased significantly to 6.38±1.74, indicating restored finger sensory function. All postoperative changes were statistically significant (all $P < 0.001$) (**Table 4**).

*Correlation analysis of postoperative functional indicators*

Pearson correlation analysis based on 6-month postoperative follow-up data showed significant correlations between all functional and symptomatic indicators. The MHQ score was positively correlated with the SF-36 score ($P < 0.001$) and negatively correlated with VAS score and 2PD value (both $P < 0.001$). The SF-36 score was negatively correlated with VAS score and 2PD value (both $P < 0.001$). The VAS score was positively correlated with the 2PD value ($P < 0.001$) (**Table 5**).

*Stratified analysis of hand function recovery*

All 186 patients completed 12-month follow-up, and 158 patients achieved standard hand function recovery, with a cumulative recovery rate of 84.95%. CIF curve analysis showed significant inter-group differences in hand function recovery. Patients with injury-to-operation time ≤ 6 hours and those with incomplete avulsion injuries had significantly higher hand function recovery rates than their corresponding counterparts (both $P = 0.003$). Patients with vascular injury length ≤ 3 cm also achieved better functional recovery than those with vascular injury length > 3 cm ($P = 0.032$). No significant differences in hand function recovery were observed in stratified analyses of gender, age, injury cause, injured finger type, multiple finger injury, infection status and skin soft tissue defect (all $P > 0.05$) (**Figure 1**).

*Variable screening via LASSO regression*

Ten candidate variables were included in the LASSO regression model with 10-fold cross-validation. The optimal penalty parameters were lambda.min = 0.002 and lambda.1se = 0.023. To reduce overfitting risk, lambda.1se was adopted for model construction. Finally, six variables with non-zero regression coefficients were screened out as effective predictive factors: age, injury-to-operation time, avulsion type, injured finger type, multiple finger injury, and vascular injury length. The remaining four variables (gender, injury cause, infection status, skin and soft tissue defect) had zero coefficients and showed no predictive value for hand function recovery (**Figure 2**).

*Prognostic influencing factor analysis*

Univariate and multivariate logistic regression analyses confirmed six independent prognostic factors for hand function recovery. Short injury-to-operation time (OR = 0.195, 95% CI: 0.083-0.456, $P < 0.001$), incomplete avulsion (OR = 0.282, 95% CI: 0.120-0.665, $P = 0.004$) and

**Table 3.** Detailed management and prognosis of complications

| Complication | Treatment | Prognosis | Prevention |
|---|---|---|---|
| Vascular crisis (n = 19) | Surgical re-exploration; thrombectomy; re-anastomosis or graft extension; topical papaverine; systemic heparinization | 13/19 (68.42%) salvaged; 6/19 (31.58%) necrosis | Trim intima to healthy level; tension-free anastomosis; ≥ 2 venous anastomoses; antispasmodic + anticoagulant; monitor q1h for 72 h |
| Persistent swelling > 7 d (n = 28) | Limb elevation; lymphatic massage; intermittent pneumatic compression; loosening of dressings | All resolved within 14-21 d | Ensure ≥ 2 patent venous anastomoses; avoid tight bandaging; postoperative elevation protocol |
| Incision infection (n = 8) | Wound culture + debridement; targeted IV antibiotics; delayed closure or VAC therapy | 7/8 resolved within 2 wk; 1/8 required skin graft | Thorough debridement; perioperative prophylactic antibiotics; sterile technique |
| Poor wound healing (n = 12) | Conservative: dressing changes + growth factor gel; Surgical: debridement + local flap (5) or skin graft (3); secondary intention (4) | All healed; mean 3.5 wk (range 2-6 wk) | Assess skin viability; avoid excessive closure tension; optimize glycemic control; smoking cessation |

**Table 4.** Functional and pain indicators before and after surgery

| Indicator | Preoperative | 6 Months Postoperative | *P* value |
|---|---|---|---|
| VAS | 7.77±1.05 | 1.94±0.66 | < 0.001 |
| SF-36 | 53.58±8.57 | 78.88±7.98 | < 0.001 |
| MHQ | 49.74±9.17 | 82.55±6.29 | < 0.001 |
| 2PD (mm) | 10.95±2.35 | 6.38±1.74 | < 0.001 |

Note: VAS, Visual analogue scale; SF-36, Short Form-36 Health Survey; MHQ, Michigan Hand Questionnaire; 2PD, Two-point discrimination.

**Table 5.** Correlation analysis of postoperative functional indicators

| Indicator | MHQ Score | SF-36 Score | VAS Score | 2PD |
|---|---|---|---|---|
| MHQ Score | 1.000 | 0.684 | -0.657 | -0.609 |
| SF-36 Score | 0.684 | 1.000 | -0.635 | -0.592 |
| VAS Score | -0.657 | -0.635 | 1.000 | 0.593 |
| 2PD | -0.609 | -0.592 | 0.593 | 1.000 |

Note: VAS, Visual analogue scale; SF-36, Short Form-36 Health Survey; MHQ, Michigan Hand Questionnaire; 2PD, Two-point discrimination.

short vascular injury length (OR = 0.317, 95% CI: 0.139-0.726, P = 0.007) were protective factors for functional recovery. Advanced age (OR = 1.052, 95% CI: 1.010-1.096, P = 0.015) and thumb injury (OR = 2.453, 95% CI: 1.065-5.648, P = 0.035) were adverse prognostic factors. Multiple finger injury showed no significant independent effect after multivariate correction.

The regression coefficients of the final LASSO model were as follows: age = 0.115, injury-to-operation time ≤ 6 hours = -2.887, incomplete avulsion = -0.662, thumb injury = 0.065, multiple finger injury = -0.070, vascular injury length ≤ 3 cm = -0.674 (**Table 6**).

*Predictive model efficacy verification*

The LASSO-based prognostic model showed excellent discriminatory ability with an AUC of 0.913 (95% CI: 0.872-0.963). DCA results indicated that within the threshold probability of 15-70%, the model-guided clinical decision-making provided higher net clinical benefit than the "full treatment" and "no treatment" strategies, confirming the high clinical application value of the model (**Figure 3**).

*Establishment of avulsion injury grading and tiered management strategy*

Based on the six prognostic risk factors screened by LASSO regression, a three-tier severity grading system for avulsed amputated finger injuries and corresponding tiered diagnosis and treatment strategies were established (**Table 7**).

## Discussion

This single-center retrospective study systematically analyzed 186 patients with avulsed

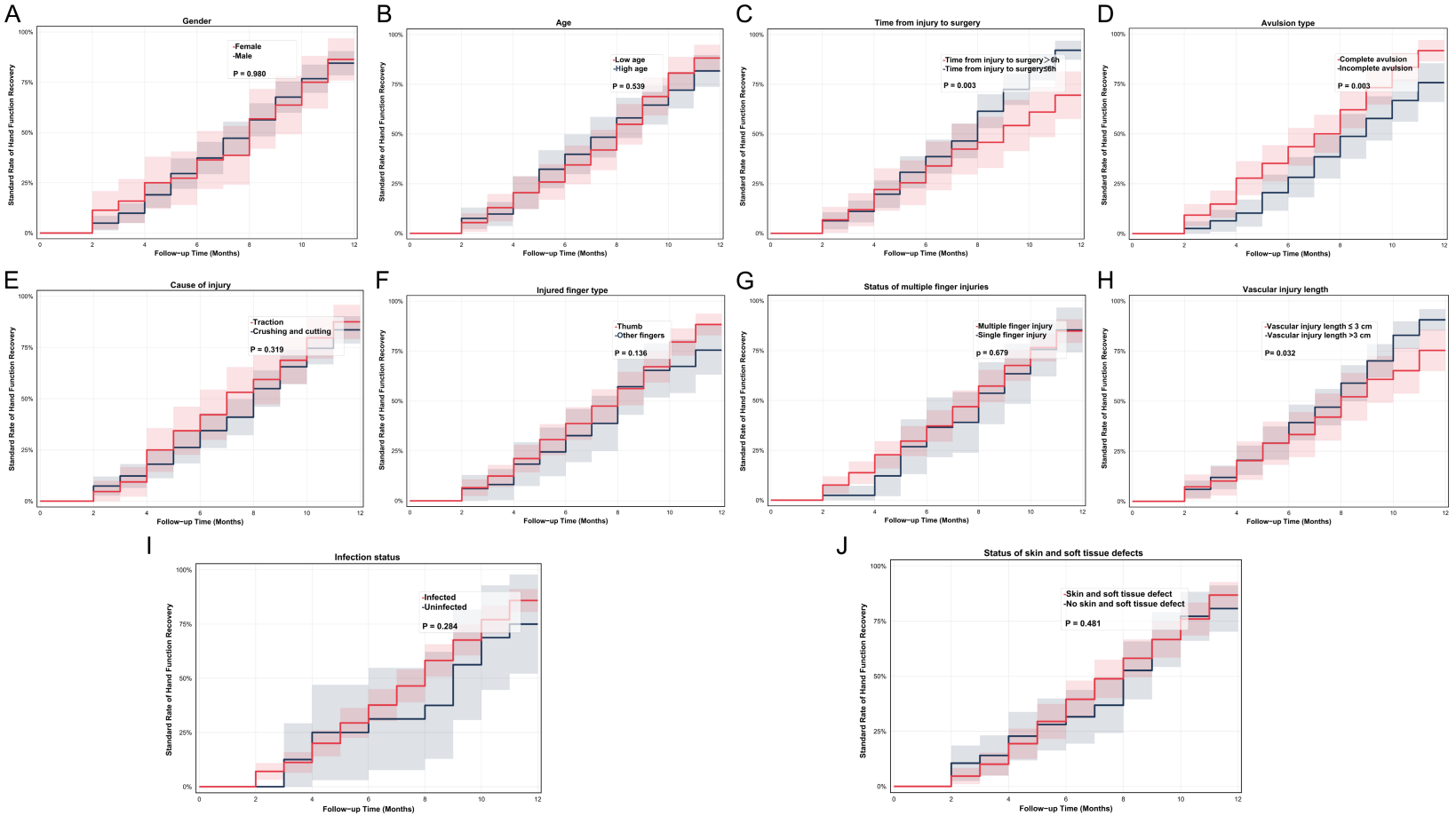



**Figure 1.** Cumulative incidence function (CIF) curves of hand function recovery by subgroup. A. CIF curves for hand function recovery in patients of different genders. B. CIF curves for hand function recovery in patients of different age groups. C. CIF curves for hand function recovery stratified by the time interval from injury to surgery. D. CIF curves for hand function recovery in patients with different avulsion types. E. CIF curves for hand function recovery stratified by different injury causes. F. CIF curves for hand function recovery in patients with different injured finger types. G. CIF curves for hand function recovery between patients with and without multiple finger injuries. H. CIF curves for hand function recovery stratified by different vascular injury lengths. I. CIF curves for hand function recovery between patients with and without infection. J. CIF curves for hand function recovery between patients with and without skin and soft tissue defects.

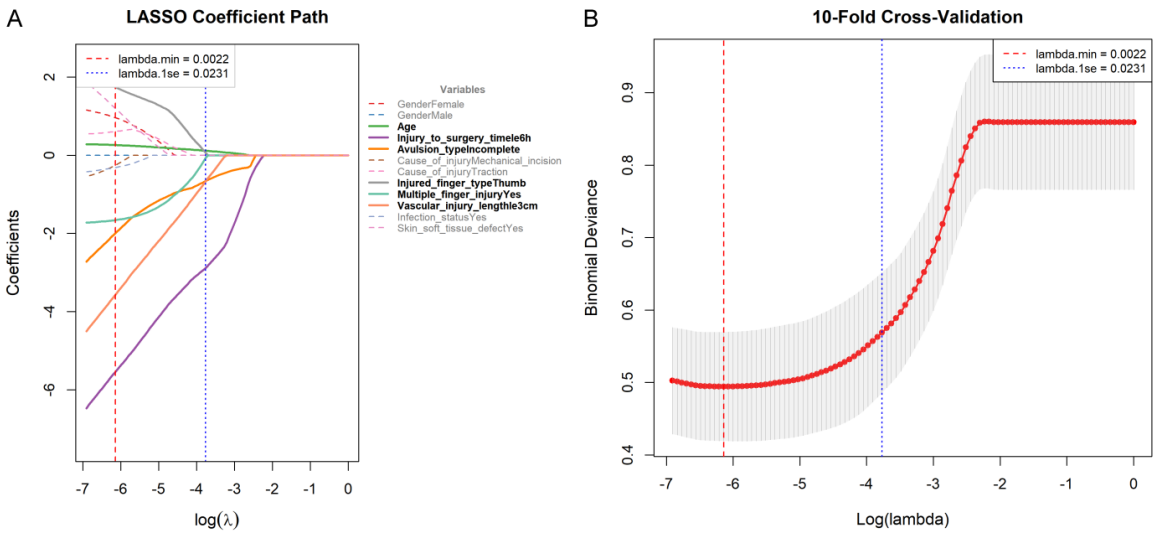



**Figure 2.** Results of variable selection via LASSO regression. A. LASSO coefficient path plot showing the shrinkage trend of each variable's coefficient with the increase of λ value; B. 10-fold cross-validation curve with the positions corresponding to lambda.min and lambda.1se marked.

amputated fingers treated with microsurgical vascular and nerve repair combined with FVG. The clinical outcomes confirmed that this combined surgical protocol achieves a high finger survival rate of 94.09% and significantly improves postoperative pain, quality of life and hand sensory and motor function. Different from previous studies that only focused on finger survival, this study established a multidimensional, patient-centered efficacy evaluation system and constructed a validated prognostic prediction model and injury grading system, providing comprehensive clinical evidence for standardized treatment of avulsed finger amputations.

Avulsed finger amputations are characterized by extensive vascular intimal contusion and severe soft tissue damage, which make direct vascular anastomosis difficult and lead to a lower natural replantation success rate than clean incised amputations [16]. This study verified that standardized FVG can effectively bridge vascular defects and eliminate anastomotic tension, achieving a significantly higher finger survival rate than conventional repair techniques reported in community hospital studies [17, 18]. This fully demonstrates that FVG is an effective technical solution to overcome the surgical bottleneck of avulsed finger replantation.

In terms of functional efficacy, this study confirmed that patients obtained significant pain relief and quality of life improvement after surgery. The postoperative VAS score decreased from 7.77 to 1.94, and the SF-36 and MHQ scores increased significantly, indicating substantial recovery of daily living and hand function. Correlation analysis further proved that hand function recovery was closely associated with pain relief and improved quality of life, which is consistent with the findings of Kuret et al. [19]. Severe finger injury can damage grip and pinch function and reduce patients' quality of life, so comprehensive functional recovery evaluation is essential for judging surgical efficacy.

LASSO regression screening identified six core prognostic factors for hand function recovery. Injury-to-operation time was the strongest protective factor. Surgery performed within 6 hours after injury significantly improved prognosis, which is consistent with the pathophysiological mechanism of ischemia-reperfusion injury and previous research conclusions [20-22]. Shortening preoperative waiting time and opening an emergency green channel are critical to improving patient outcomes.

Incomplete avulsion injury and vascular injury length ≤ 3 cm were protective factors for functional recovery. Incomplete avulsion retains partial soft tissue continuity, which facilitates local microcirculation reconstruction and nerve regeneration. FVG can effectively compensate for the adverse effects of long-segment vascu-

**Table 6.** Prognostic influencing factor analysis

| Indicator | Hand Function Recovery (n = 158) | No Recovery (n = 28) | Univariate Analysis | | Multivariate Analysis | |
|---|---|---|---|---|---|---|
| | | | OR | P | Penalized Coef. | Selected |
| Gender | | | 1.161 (0.439-3.074) | 0.764 | | No |
| Male | 120 | 22 | | | | |
| Female | 38 | 6 | | | | |
| Age (years) | 39.04±9.79 | 44.29±12.04 | 1.052 (1.010-1.096) | 0.015 | +0.115 | Yes |
| Time from injury to surgery | | | 0.195 (0.083-0.456) | < 0.001 | -2.887 | Yes |
| ≤ 6 h | 117 | 10 | | | | |
| > 6 h | 41 | 18 | | | | |
| Avulsion type | | | 0.282 (0.120-0.665) | 0.004 | -0.662 | Yes |
| Complete | 59 | 19 | | | | |
| Incomplete | 99 | 9 | | | | |
| Cause of injury | | | 1.690 (0.557-5.122) | 0.354 | | No |
| Traction | 73 | 13 | | | | |
| Crush | 56 | 8 | | | | |
| Mechanical incision | 29 | 7 | | | | |
| Injured finger type | | | 2.453 (1.065-5.648) | 0.035 | +0.065 | Yes |
| Thumb | 37 | 12 | | | | |
| Other fingers | 121 | 16 | | | | |
| Multiple finger injury | | | 0.958 (0.361-2.548) | 0.932 | -0.070 | Yes |
| Yes | 35 | 6 | | | | |
| No | 123 | 22 | | | | |
| Vascular injury length | | | 0.317 (0.139-0.726) | 0.007 | -0.674 | Yes |
| ≤ 3 cm | 106 | 11 | | | | |
| > 3 cm | 52 | 17 | | | | |
| Infection status | | | 2.028 (0.604-6.808) | 0.253 | | No |
| Yes | 12 | 4 | | | | |
| No | 146 | 24 | | | | |
| Skin and soft tissue defect | | | 1.575 (0.685-3.622) | 0.285 | | No |
| Yes | 46 | 11 | | | | |
| No | 112 | 17 | | | | |

Note: LASSO, Least Absolute Shrinkage and Selection Operator; OR, odds ratio; CI, confidence interval; Coef, coefficient. Penalized coefficients are shrunken estimates from the LASSO model at lambda.1se = 0.023. Variables with coefficients shrunk to zero by LASSO are marked "No" in the Selected column.

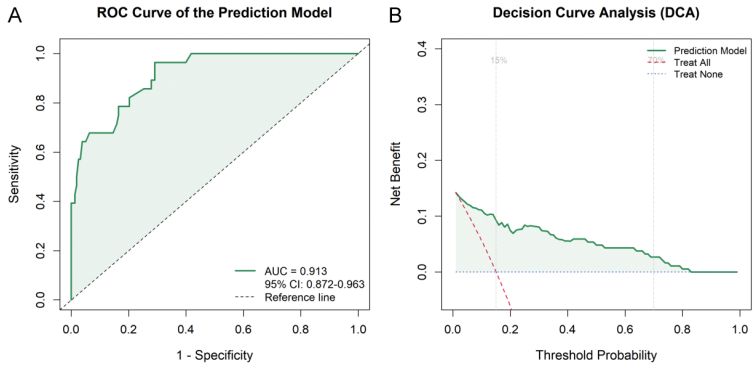



**Figure 3.** Efficacy evaluation of the prediction model. Note: A. ROC curve; B. Decision curve analysis (DCA).

lar defects and reduce the impact of vascular injury severity on prognosis. Advanced age and thumb injury were adverse prognostic factors, which were attributable to declined tissue regeneration ability in elderly patients and higher surgical complexity and functional requirements of thumb reconstruction.

The constructed prediction model had an AUC of 0.913, indicating excellent discriminatory performance. DCA further verified that the model can bring stable net clinical benefits for clinical decision-making, which is suitable for preoperative prognostic assessment and individualized rehabilitation

**Table 7.** Avulsion injury grading and tiered management strategy

| Grade | Risk Profile | Surgical Protocol | Monitoring Protocol | Rehabilitation Protocol |
|---|---|---|---|---|
| Grade I (Low risk) | Time from injury to surgery ≤ 6 hours combined with incomplete avulsion injury | Standard free venous grafting; anastomosis of one artery and two veins | Monitoring every 2 hours for 48 consecutive hours; hospital discharge 5-7 days after surgery | Passive functional training initiated 3-5 days postoperatively; active training started at postoperative week 2; sensory rehabilitation training commenced at postoperative week 4 |
| Grade II (Moderate risk) | Time from injury to surgery ≤ 6 hours combined with complete avulsion injury, or time from injury to surgery > 6 hours combined with incomplete avulsion injury | Enhanced free venous grafting; anastomosis of at least two veins; nerve grafting performed for nerve defects longer than 1 cm | Hourly monitoring for 72 consecutive hours; 7-day anticoagulant therapy; hospital stay of 7-10 days | Passive training carried out 7-10 days postoperatively; active training initiated at postoperative week 3; sensory functional rehabilitation conducted under physician guidance |
| Grade III (High risk) | Time from injury to surgery > 6 hours combined with complete avulsion injury | Aggressive replantation with anastomosis of at least three veins; amputation combined with secondary toe-to-finger reconstruction is an alternative if the estimated replant survival rate is less than 50% | Stepwise intensive monitoring for 72-96 hours; 10-day anticoagulation with low-molecular-weight heparin | Individualized rehabilitation regimen; functional exercise delayed for 2-3 weeks after surgery; rehabilitation follow-up lasts no less than 6 months |

guidance for patients with avulsed amputated fingers.

This study has several limitations. First, this was a single-center retrospective study, which inevitably has selection, information and follow-up biases. Propensity score matching was not used to balance confounding factors, and unobserved residual confounding effects may exist despite LASSO variable optimization. Multicenter prospective studies with causal inference methods are required to validate the results.

Second, although the sample size met the precalculated standard, it remained limited for predictive model construction. External validation with independent cohorts is required before clinical promotion of the model and injury grading system.

Third, the 12-month follow-up period cannot fully reflect long-term hand functional recovery. Longer follow-up observation is needed in future studies.

Fourth, the current LASSO model did not incorporate the nonlinear effects and interaction terms of variables. Further optimization via machine learning algorithms can improve the predictive accuracy of the model.

In conclusion, microsurgical vascular and nerve repair combined with FVG is a safe and effective treatment for avulsed amputated fingers. This surgical protocol achieves high finger survival rate and significant improvements in pain, quality of life and hand function. The identified prognostic factors and validated prediction model can support individualized surgical decision-making, risk stratification and targeted rehabilitation intervention, which have good clinical popularization value.

## Disclosure of conflict of interest

None.

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