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Original Article

Prognostic value of multimodal neurophysiological - ultrasound assessments in median and ulnar nerve injury repair

Xin Chen[1], Jinmei Gao[2], Yu Yuan[2]

[1]Department of Electromyogram, Tianjin Hospital, Tianjin 300211, China; [2]Department of Ultrasound, Tianjin Hospital, Tianjin 300211, China

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Abstract: Objective: To investigate whether combining neurophysiological assessments with high-resolution ultrasound (HRUS) enhances the prediction of functional recovery and prognosis in patients undergoing surgical repair for median or ulnar nerve injury. Methods: This retrospective study included 315 patients who underwent surgical repair for median or ulnar nerve injuries between February 2013 and February 2023. Six months post-surgery, all patients underwent neurophysiological and ultrasound evaluations. Based on British Medical Research Council (BMRC) criteria, patients were categorized into good prognosis (n = 177) and poor (n = 138) prognosis groups. Key factors like distal motor latency (DML), sensory conduction velocity (SCV), and neural cross-sectional area were analyzed. Logistic regression and receiver operating characteristic (ROC) curve analyses were performed to assess their predictive values for functional recovery. Results: Compared to the poor prognosis group, the good prognosis group showed significantly better neurophysiological measurements, including shorter DML (median nerve: 4.66 ± 0.62 vs. 4.89 ± 0.85 ms; ulnar nerve: 3.29 ± 0.35 vs. 3.42 ± 0.38 ms), higher SCV (median: 44.03 ± 4.22 vs. 42.27 ± 5.13 m/s; ulnar: 44.25 ± 6.24 vs. 42.51 ± 7.18 m/s), and faster motor conduction velocity ($P < 0.05$). HRUS revealed smaller cross-sectional areas and lower nerve swelling rates in the good prognosis group (both $P < 0.05$). Logistic regression identified DML, SCV, and nerve swelling rate as independent predictors of functional recovery. The combined model demonstrated high predictive accuracy with an AUC of 0.967. Conclusion: Combining neurophysiological testing and HRUS offers a comprehensive and accurate approach for assessing postoperative recovery in median and ulnar nerve injuries, thereby improving prognostic accuracy and facilitating personalized treatment strategies.

Keywords: Peripheral nerve injuries, median nerve, ulnar nerve, neurophysiology, high-resolution ultrasound, prognosis

Introduction

Injuries to peripheral nerves, particularly the median and ulnar nerves, present a considerable clinical challenge. These injuries substantially impair patients' hand function and overall quality of life [1, 2]. The median nerve is responsible for sensation and movement in the forearm and hand, while the ulnar nerve controls intrinsic hand muscles. Both are essential for fine motor skills and coordinated hand movements. Damage to these nerves can cause loss of sensation, muscle weakness, and reduced dexterity, significantly affecting daily activities and occupational performance. Therefore, timely and accurate diagnosis, along with appropriate surgical intervention, is critical for optimizing functional recovery [3-5].

Although surgical repair remains the primary treatment, functional outcomes vary considerably among individuals. This variability is influenced by several key factors, including the mechanism and severity of injury, timing of surgical intervention, and post-surgical rehabilitation strategies. A thorough understanding of these factors is essential for developing tailored treatment plans, improving patient outcomes and refining surgical strategies [6-8].

Traditionally, prognosis assessment has relied heavily on clinical examination and patient-

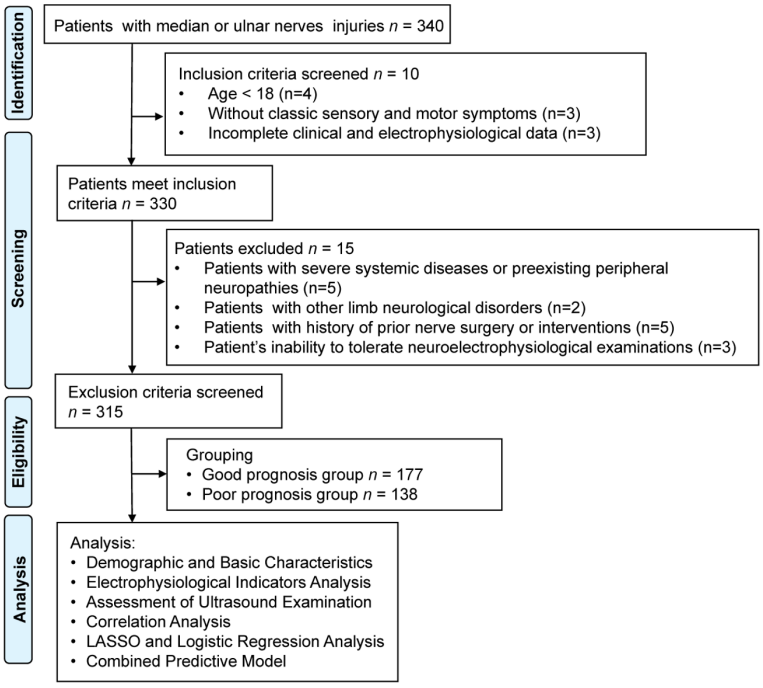

Figure 1. Patient selection process.

reported symptoms [9, 10]. In recent years, new technologies, including electromyography (EMG) and nerve conduction studies (NCS), have become standard for evaluating nerve function [11, 12]. These tests measure the electrical activity of muscles and the conduction velocity of nerves, aiding in the detection of nerve injury and the prediction of recovery. However, these tests provide limited information on the structural integrity of nerves and surrounding tissues.

High-resolution ultrasound (HRUS) has emerged as a valuable, non-invasive tool for evaluating peripheral nerve injuries. It enables real-time visualization of nerve structures, allowing assessment of nerve size, continuity, and surrounding tissues. It is effective for detecting nerve compressions and structural abnormalities, as well as in monitoring postoperative recovery. When combined with neurophysiologic assessments, HRUS offers a more comprehensive evaluation, potentially improving prognostic accuracy and guiding personalized rehabilitation strategies [13-15].

Although both neurophysiological assessments and HRUS have advanced in recent years, the extent to which their combined application can improve prognostic prediction after median and ulnar nerve repair remains unclear. Previous studies have evaluated the utility of neurophysiological testing alone in nerve injury assessment, while others have focused on the role of HRUS independently [16, 17]. However, studies exploring the synergistic value of integrating these modalities remain limited, especially in the postoperative setting, for predicting functional recovery.

This study addresses this gap by jointly applying neurophysiologic and ultrasonographic assessments to evaluate recovery following surgical repair of median and ulnar nerve injuries. Such an integrative approach may facilitate individualized treatment planning, optimize rehabilitation strategies, and ultimately enhance functional outcomes and quality of life in patients with peripheral nerve injuries.

Materials and methods

Patient selection

A total of 315 patients who underwent surgical repair of median or ulnar nerve injuries at Tianjin Hospital between February 2013 and February 2023 were retrospectively enrolled. Prognosis was evaluated 6 months postoperatively using the British Medical Research Council (BMRC) criteria [18] for motor and sensory recovery following peripheral nerve injury. The patients were categorized into either a good prognosis group (n = 177) or a poor prognosis group (n = 138) (**Figure 1**).

Inclusion criteria: (1) age between 18 and 80 years; (2) confirmed median or ulnar nerve injury classified as Grade III-V requiring surgical repair; (3) repair and anastomosis of the median or ulnar nerves performed at Tianjin Hospital; (4) presence of classic sensory and motor deficits; (5) availability of complete clinical and electrophysiological data with a minimum 6-month postoperative follow-up; and (6) unilateral limb nerve injury.

Exclusion criteria: (1) severe systemic diseases (e.g., uncontrolled diabetes, autoimmune disorders) or preexisting peripheral neuropathies (e.g., diabetic neuropathy); (2) other neurological disorders of the affected limb (e.g., cervical radiculopathy, brachial plexopathy); (3) history of prior nerve surgery or reconstructive interventions (e.g., tendon transfers); (4) neurological damage due to non-traumatic causes (e.g., tumors, infections); (5) intolerance to neuroelectrophysiological examinations; or (6) incomplete 6-month postoperative follow-up data.

The severity of nerve injury was categorized into five grades [19]. Grade I and II injuries involve only the myelin sheath and axons, with preserved nerve fiber integrity, thus obviating the need for surgery. These injuries generally undergo spontaneous repair within approximately two months, resulting in favorable prognosis. In contrast, Grade III to V injuries present varying degrees of disruption to the endoneurium, perineurium, and epineurium, leading to partial or complete discontinuity of nerve fibers. Such injuries necessitate surgical intervention to realign displaced fibers or restore continuity, since spontaneous regeneration is not possible without intervention. All patients included in this study sustained Grade III to V injuries.

This retrospective study was approved by the Ethics Committee of Tianjin Hospital. As it involved analysis of existing medical records without direct patient contact or intervention, and all data were de-identified to protect patient privacy, the requirement for individual informed consent was waived.

Data extraction

(1) Baseline demographic and clinical data were collected for all participants, including sex, age, body mass index (BMI), and side of injury. Additional variables included injury characteristics, surgical details, and postoperative outcomes. Trained staff used standardized forms to ensure consistency, and all data were independently verified by two reviewers to minimize errors.

Six months after surgery, all patients underwent standardized neurophysiological and HRUS evaluations. Measured findings included distal motor latency (DML), distal sensory latency (DSL), sensory conduction velocity (SCV), motor conduction velocity (MCV), sensory nerve action potential (SNAP), compound muscle action potential (CMAP), nerve cross-sectional area, and nerve swelling rate.

(2) Electromyography (EMG) and Nerve Conduction Studies (NCS): Patients were examined in a supine position. Concentric needle electrodes used to record insertional potentials, resting potentials, motor unit potentials during slight muscle contraction, and recruitment potentials during maximal contraction. Electrical stimulation was applied to muscles innervated by the affected nerves to elicit maximal action potentials. The recording electrodes were placed 2-3 cm apart. Nerve conduction amplitudes and velocities were measured using standard protocols.

(3) High-Resolution Ultrasound (HRUS) Examination: Patients were positioned either supine or seated. Longitudinal and transverse scans were performed along the course of the affected nerve to observe the injury site morphology and continuity. The cross-sectional area (CSA) of the nerve was measured at the lesion site and at a proximal, unaffected site. Nerve swelling rate was calculated as the ratio of CSA at the lesion site to CSA at the proximal site.

Outcome measures

The primary outcome measure was motor function grade according to the BMRC criteria, with M4 and M3 indicating complete or near-complete functional restoration. Secondary outcome measures included sensory function grade, DML, DSL, SCV, MCV, SNAP, and CMAP.

Patients were categorized into two groups based on their BMRC level: a good prognosis group (n = 177) and a poor prognosis group (n = 138). A poor prognosis was defined as sensory function ≤ S2 and motor function ≤ M2, while higher scores were classified as a good prognosis [20]. The detailed BMRC scoring criteria are shown in **Tables 1** and **2**.

Statistical analysis

Statistical analyses were performed using SPSS 21.0 (IBM Corp.) and R software (version 4.2.2). Continuous variables were expressed as mean ± standard deviation (SD) and compared between groups using independent sam-

Table 1. Motor function grading according to BMRC

Grade	Description
M4	Complete functional restoration, able to move against gravity plus additional resistance
M3	Functional movement against gravity alone
M2	Slight muscle contraction without resistance
M1	Minimal detectable contraction
M0	Absence of muscle contraction

Table 2. Sensory function grading according to BMRC

Grade	Description
S4	Full recovery with normal tactile and pain perception
S3	Improved sensation
S2	Partial improvement in pain perception
S1	Minimal sensory recovery, only pain perception
S0	No sensation

ples t-tests. Categorical variables were presented as frequencies (percentages) and analyzed using chi-square tests. Spearman's correlation analysis was employed to examine associations between neurophysiologic/ultrasound measurements and prognosis.

To identify key prognostic predictors, the least absolute shrinkage and selection operator (LASSO) regression with tenfold cross-validation was applied to optimize the penalty parameter (lambda) and minimize overfitting. Variables with non-zero coefficients were retained for subsequent analyses.

Univariate logistic regression was then conducted to evaluate individual predictors. Multivariable logistic regression was performed using a forward stepwise approach based on the variables selected by the LASSO regression ($P < 0.05$ for entry). Variables were retained if they remained significant ($P < 0.05$) after adjustment for covariates and removed if $P > 0.10$. Adjusted odds ratios (ORs) and 95% confidence intervals (CIs) were calculated.

Receiver operating characteristic (ROC) curves were generated to assess the discriminative performance of individual predictors and their combined model. Optimal cutoff values were determined using Youden's index, and sensitivity, specificity, area under the curve (AUC), and F1 scores were reported. A nomogram integrating significant predictors was developed to facilitate risk stratification. Model calibration was assessed using calibration curves, while decision curve analysis (DCA) and clinical impact curves (CIC) were used to evaluate clinical utility by quantifying net benefits across threshold probabilities. Statistical significance was set at a two-tailed $P < 0.05$.

Results

Demographic and basic data

A total of 315 patients were included, comprising 177 in the good prognosis group and 138 in the poor prognosis group. As shown in **Table 3**, gender distribution ($P = 0.454$) and mean age ($P = 0.41$) were comparable between the two groups. BMI, type of nerve injury, and degree of nerve damage showed no significant differences between groups ($P > 0.05$ for all). Laterality of injury (left vs. right) and the cause of injury (traumatic vs. nontraumatic) also revealed no significant differences ($P > 0.05$). Furthermore, lifestyle factors, including smoking history, alcohol consumption, family history of neurological disease, and educational level, did not differ significantly between groups.

These findings indicated that demographic and baseline clinical characteristics were not significantly associated with postoperative prognosis in this patients.

Electrophysiological indicators

Significant differences in electrophysiological data were observed between the two groups for both median and ulnar nerves (**Figure 2** and **Table 4**).

For the median nerve, the good prognosis group demonstrated: shorter distal motor latency (DML) (4.66 ± 0.62 ms vs. 4.89 ± 0.85 ms; $P = 0.006$), shorter distal sensory latency

Table 3. Comparison of general patient information between the two groups

Variable	Good prognosis (n = 177)	Poor prognosis (n = 138)	t/χ^2	P
Gender [n (%)]			0.561	0.454
Male	115 (64.97%)	84 (60.87%)		
Female	62 (35.03%)	54 (39.13%)		
Age (years)	36.46 ± 13.15	35.39 ± 9.84	0.825	0.41
BMI (kg/m^2)	21.85 ± 2.62	22.13 ± 2.67	0.923	0.357
Type of nerve injury [n (%)]			1.776	0.411
Median nerve	61 (34.46%)	45 (32.61%)		
Ulnar nerve	59 (33.33%)	39 (28.26%)		
Both	57 (32.2%)	54 (39.13%)		
Type of injury [n (%)]			0.095	0.758
Open	79 (44.63%)	64 (46.38%)		
Closed	98 (55.37%)	74 (53.62%)		
Degree of nerve damage [n (%)]			0.077	0.962
III	63 (35.59%)	51 (36.96%)		
IV	58 (32.77%)	45 (32.61%)		
V	56 (31.64%)	42 (30.43%)		
Affected side [n (%)]			0.381	0.537
Left	90 (50.85%)	75 (54.35%)		
Right	87 (49.15%)	63 (45.65%)		
Cause of injury [n (%)]			0.174	0.676
Traumatic	108 (61.02%)	81 (58.7%)		
Nontraumatic	69 (38.98%)	57 (41.3%)		
Course of disease (d)	32.53 ± 3.48	31.97 ± 3.16	1.471	0.142
Smoking history [n (%)]	93 (52.54%)	81 (58.7%)	1.187	0.276
Alcohol consumption history [n (%)]	86 (48.59%)	75 (54.35%)	1.03	0.31
Family history of neurological disease [n (%)]	41 (23.16%)	35 (25.36%)	0.205	0.651
Educational level [n (%)]			1.069	0.586
Junior high school and below	73 (41.24%)	60 (43.48%)		
High school/technical secondary school	58 (32.77%)	49 (35.51%)		
College or above	46 (25.99%)	29 (21.01%)		

BMI: Body mass index.

(DSL) (2.87 ± 0.93 ms vs. 3.11 ± 1.04 ms; P = 0.026), higher sensory conduction velocity (SCV) (44.03 ± 4.22 m/s vs. 42.27 ± 5.13 m/s; P = 0.001), superior motor conduction velocity (MCV) (45.65 ± 7.36 m/s vs. 43.51 ± 6.82 m/s; P = 0.009), greater sensory nerve action potential (SNAP) (7.07 ± 2.26 μV vs. 6.39 ± 2.14 μV; P = 0.008), and greater compound muscle action potential (CMAP) amplitude (7.65 ± 0.69 mV vs. 7.41 ± 0.63 mV; P = 0.002).

For the ulnar nerve, the good prognosis group exhibited: shorter DML (3.29 ± 0.35 ms vs, 3.42 ± 0.38 ms; P = 0.001), shorter DSL (2.68 ± 0.86 ms vs. 2.89 ± 0.82 ms; P = 0.028), higher SCV (44.25 ± 6.24 m/s vs. 42.51 ± 7.18 m/s; P = 0.022), higher MCV (45.72 ± 6.14 m/s vs. 43.71 ± 9.55 m/s; P = 0.033), greater SNAP amplitude (7.51 ± 3.14 μV vs. 6.75 ± 2.92 μV; P = 0.028), and greater CMAP amplitude (7.32 ± 1.54 mV vs. 6.87 ± 2.05 mV; P = 0.034).

Overall, patients with better prognoses exhibited improved electrophysiological measurements, indicating a strong association between improved conduction properties and functional recovery.

Ultrasound examination measurements

Significant differences in neural cross-sectional area (CSA) and swelling rate were observed

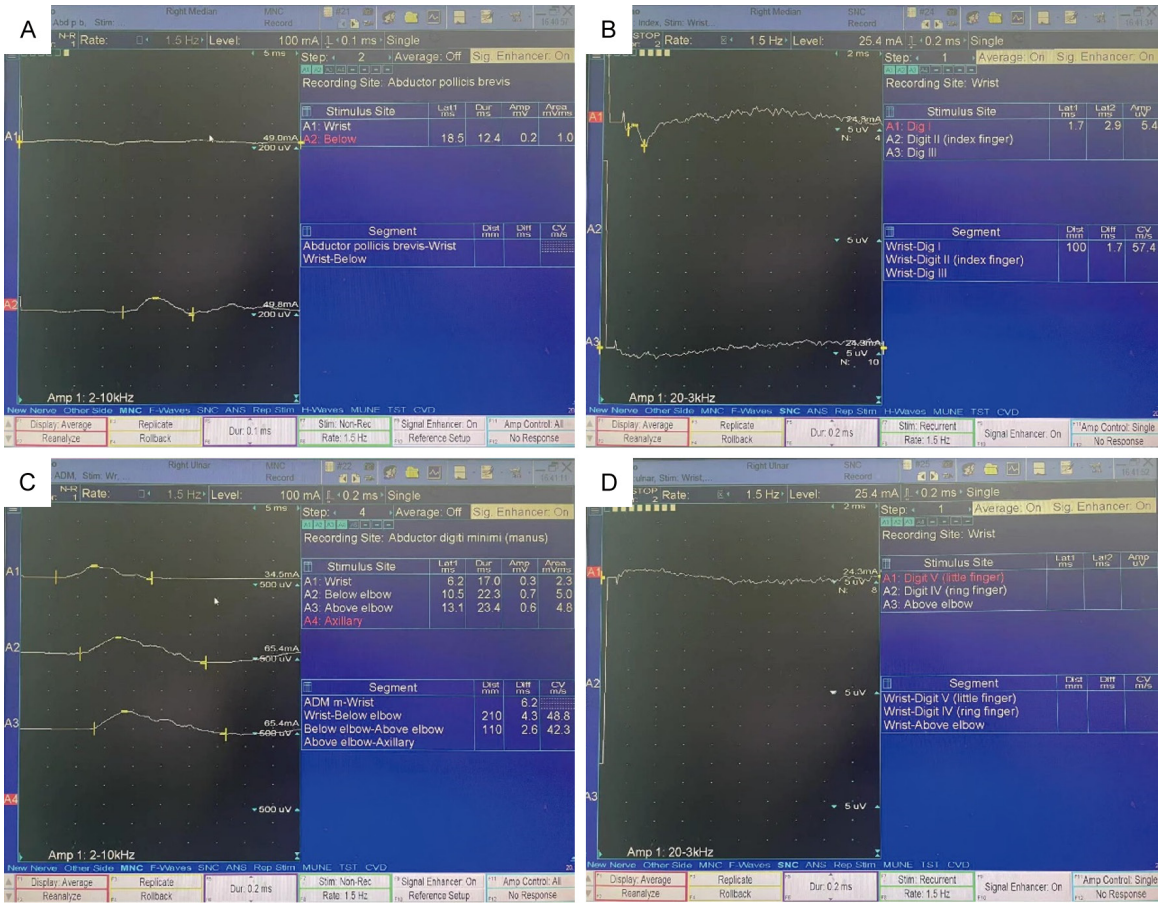

Figure 2. Representative EMG images of median and ulnar nerves. A: Motor conduction of the median nerve; B: Sensory conduction of the median nerve; C: Motor conduction of the ulnar nerve; D: Sensory conduction of the ulnar nerve.

Table 4. Electrophysiological indicators of median and ulnar nerve

Measurement	Good prognosis (n = 177)	Poor prognosis (n = 138)	t	p
Median Nerve				
DML (ms)	4.66 ± 0.62	4.89 ± 0.85	2.749	0.006
DSL (ms)	2.87 ± 0.93	3.11 ± 1.04	2.231	0.026
SCV (m·s-1)	44.03 ± 4.22	42.27 ± 5.13	3.258	0.001
MCV (m·s-1)	45.65 ± 7.36	43.51 ± 6.82	2.642	0.009
SNAP (uv)	7.07 ± 2.26	6.39 ± 2.14	2.69	0.008
CMAP (mv)	7.65 ± 0.69	7.41 ± 0.63	3.15	0.002
Ulnar Nerve				
DML (ms)	3.29 ± 0.35	3.42 ± 0.38	3.209	0.001
DSL (ms)	2.68 ± 0.86	2.89 ± 0.82	2.214	0.028
SCV (m·s-1)	44.25 ± 6.24	42.51 ± 7.18	2.295	0.022
MCV (m·s-1)	45.72 ± 6.14	43.71 ± 9.55	2.144	0.033
SNAP (uv)	7.51 ± 3.14	6.75 ± 2.92	2.202	0.028
CMAP (mv)	7.32 ± 1.54	6.87 ± 2.05	2.138	0.034

DML: Comparison of the distal motor latencies; DSL: distal sensory latencies; SCV: Perceived conduction velocity; MCV: Motion conduction velocity; SNAP: Perceived wave amplitude; CMAP: Composite muscle action potential amplitude.

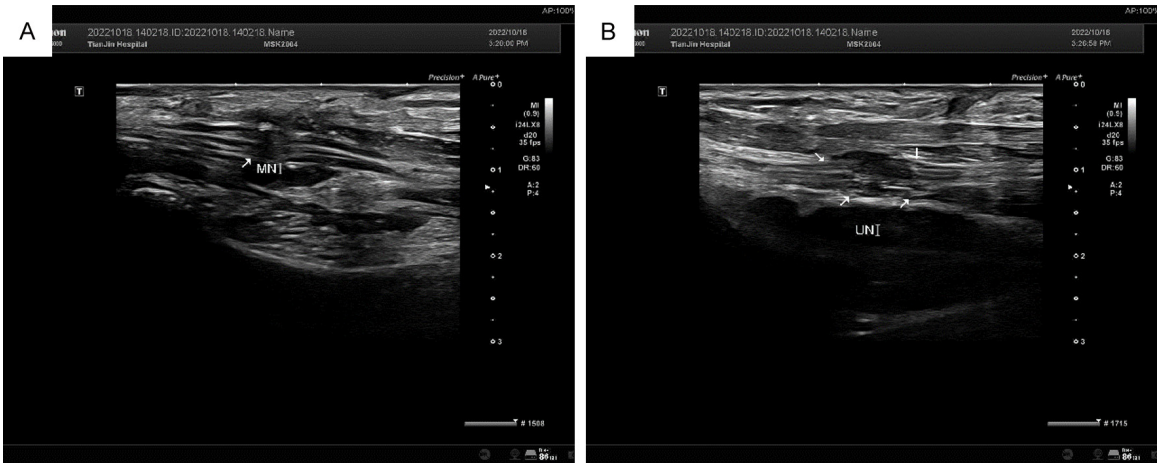

Figure 3. Representative ultrasound images of median and ulnar nerves. A: Ultrasound image of the median nerve; B: Ultrasound image of the ulnar nerve.

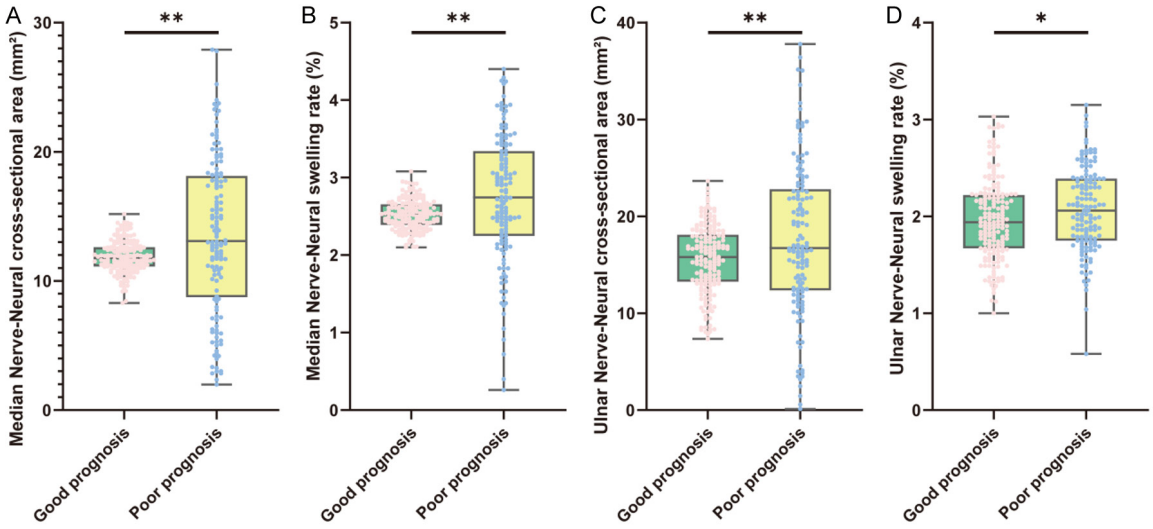

Figure 4. Comparison of ultrasound examination results for both median and ulnar nerve injuries between patients with good and poor prognosis. A: Neural cross-sectional area (CSA, mm^2) in median nerve; B: Neural swelling rate (%) in median nerve; C: Neural CSA (mm^2) in ulnar nerve; D: Neural swelling rate (%) in ulnar nerve. *: $P < 0.05$; **: $P < 0.01$.

between the good and poor prognosis groups for both median and ulnar nerves (**Figures 3** and **4**).

For the median nerve, the good prognosis group exhibited significantly smaller CSA (11.87 ± 1.24 mm^2 vs. 13.52 ± 6.07 mm^2; P = 0.002) and lower swelling rate (2.52 ± 0.19% vs. 2.74 ± 0.82%; P = 0.003).

For the ulnar nerve, the good prognosis group demonstrated substantially smaller SCA (15.54 ± 3.49 mm^2 vs. 17.62 ± 7.91 mm^2; P = 0.004) and significantly lower swelling rate (1.96 ± 0.41% vs. 2.07 ± 0.43%; P = 0.03).

Collectively, these findings highlight that smaller neural CSA and lower swelling rates are associated with better postoperative functional recovery, supporting the prognostic value of ultrasound-based data in median and ulnar nerve injuries.

Correlation analysis

Correlation analysis demonstrated significant associations between various examination

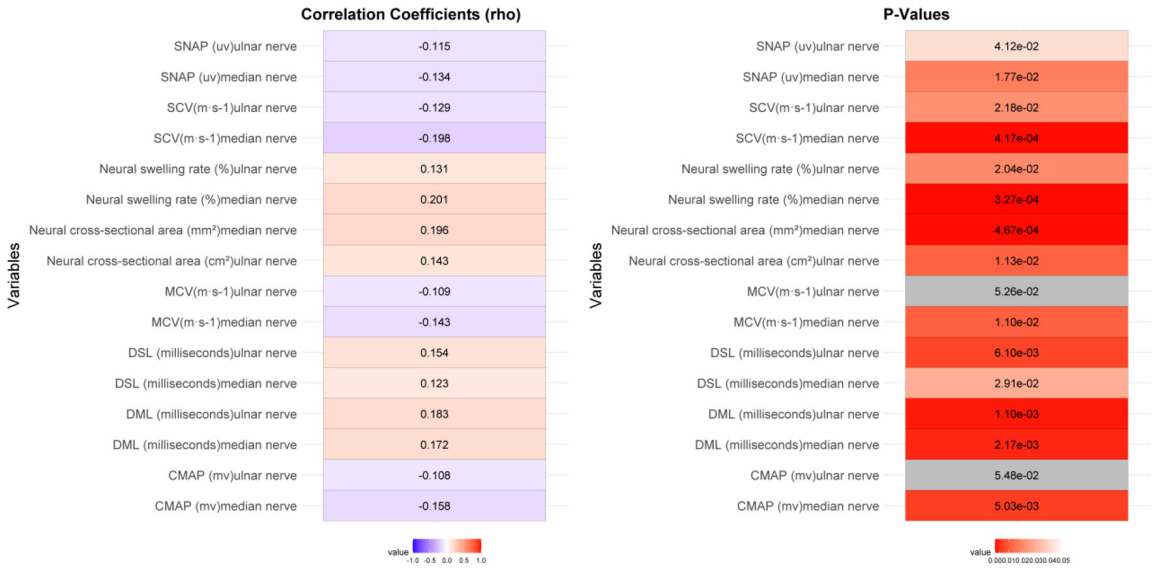

Figure 5. Correlation analysis between examined measurements and prognosis status. SNAP: Perceived wave amplitude; SCV: Perceived conduction velocity; MCV: Motion conduction velocity; DSL: distal sensory latencies; DML: Comparison of the distal motor latencies; CMAP: Composite muscle action potential amplitude.

findings and prognosis for both median and ulnar nerve injuries (**Figure 5**).

For the median nerve, DML and DSL were positively correlated with poor prognosis (rho = 0.172, P = 0.002; rho = 0.123, P = 0.029). SCV, MCV, SNAP, and CMAP were negatively correlated with poor outcomes, with SCV showing the strongest inverse correlation (rho = -0.198, P < 0.001). Additionally, larger neural CSA and higher neural swelling rates were positively associated with poorer prognoses, with neural swelling rate the strongest correlation (rho = 0.201, P < 0.001).

For the ulnar nerve, similar trends were observed. Specifically, DML and DSL were positively correlated with adverse outcomes (rho = 0.183, P = 0.001; rho = 0.154, P = 0.006). SCV, SNAP, and CMAP were inversely correlated with poor prognosis, while MCV showed a non-significant trend (P = 0.053). Both CSA and swelling rate were positively correlated with poorer outcomes.

These results suggest that specific neurophysiological and ultrasound findings can serve as predictive markers for postoperative recovery in median and ulnar nerve injuries.

Variable selection using LASSO and logistic regression analysis

LASSO regression was first employed to select prognostic variables (**Figure 6A**, **6B**). Cross-validation identified the optimal lambda value, minimizing mean squared error and retaining predictors with non-zero coefficients. This process retained DML, SCV, CSA, and swelling rate for median nerve injuries, while DML and CSA were selected for ulnar nerve injuries.

Univariate logistic regression analysis further identified several significant predictors for prognosis of both median and ulnar nerve injuries. For median nerve injuries, prolonged DML (OR = 1.571, P = 0.005) and increased neural swelling rate (OR = 2.035, P = 0.001) were associated with poor prognosis, whereas higher SCV (OR = 0.920, P = 0.001) and CMAP (OR = 0.582, P = 0.002) indicated favorable outcomes. In the multivariate analysis adjusted for LASSO-selected variables, DML (OR = 1.884, P = 0.001) and CSA (OR = 1.145, P < 0.001) remained independent predictors of poor prognosis (**Table 5**). For ulnar nerve injuries, elevated DML (OR = 2.714, P = 0.002) and neural cross-sectional area (OR = 1.063, P = 0.002) predicted adverse prognosis. In the multivariate model, DML (OR = 2.448, P = 0.024)

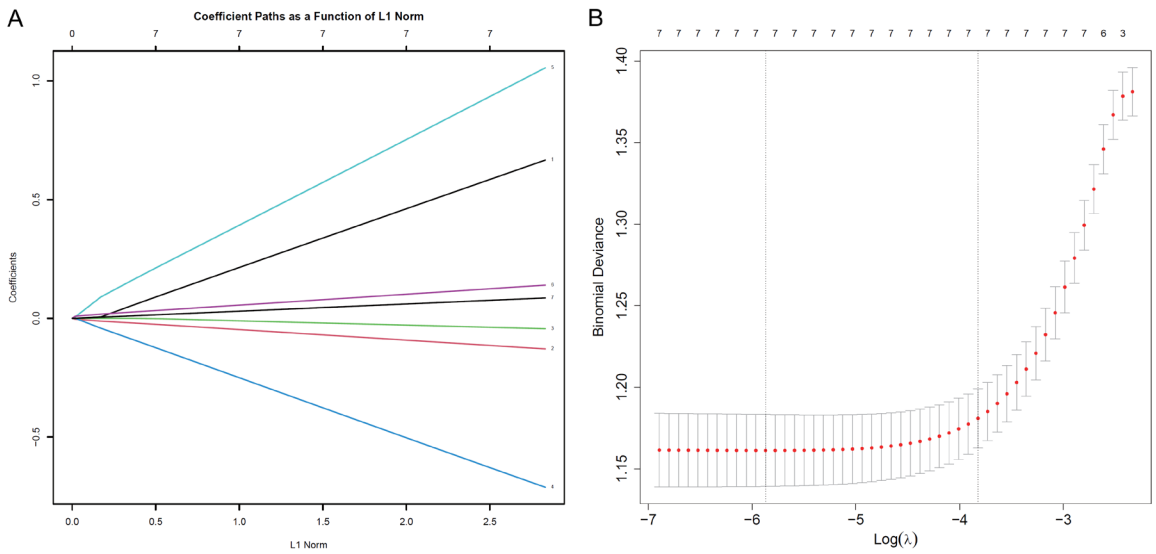

Figure 6. Feature selection via LASSO regression for prognostic modeling. A: Coefficient Profiles Across the L1 Norm Spectrum; B: Optimal Lambda Determination via Cross-Validation for LASSO Model.

Table 5. Univariate and multivariate logistic regression analyses of factors affecting the prognosis of median nerve injuries

Factor	Univariate		Multivariate	
	P	OR (95% CI)	P	OR (95% CI)
DML (ms)	0.005	1.571 (1.149-2.177)	0.001	1.884 (1.288-2.754)
DSL (ms)	0.027	1.298 (1.032-1.642)	0.234	1.186 (0.896-1.570)
SCV (m·s-1)	0.001	0.920 (0.873-0.967)	0.001	0.900 (0.845-0.959)
MCV (m·s-1)	0.010	0.959 (0.928-0.989)	0.040	0.960 (0.923-0.998)
SNAP (uv)	0.008	0.870 (0.784-0.964)	0.052	0.886 (0.783-1.001)
CMAP (mv)	0.002	0.582 (0.408-0.818)	0.002	0.514 (0.337-0.784)
Neural cross-sectional area (cm^2)	< 0.001	1.103 (1.043-1.171)	< 0.001	1.145 (1.069-1.226)
Neural swelling rate (%)	0.001	2.035 (1.340-3.181)	0.234	1.588 (0.967-2.607)

DML: Comparison of the distal motor latencies; DSL: distal sensory latencies; SCV: Perceived conduction velocity; MCV: Motion conduction velocity; SNAP: Perceived wave amplitude; CMAP: Composite muscle action potential amplitude.

was a significant prognostic factor. Other parameters such as DSL, MCV, SNAP, and swelling rate showed no significant associations with prognosis in the multivariate analysis (P > 0.05) (**Table 6**).

Overall, these results highlight emphasize that DML and neural CSA are the most robust independent predictors of postoperative prognosis for both median and ulnar nerve injuries, highlighting the complementary value of combining neurophysiological and ultrasound assessments.

ROC analysis

ROC curve analysis revealed varying discriminative capacities of neurophysiological and ultrasound data in predicting postoperative prognosis. For the median nerve, DML demonstrated moderate predictive value (AUC = 0.6, sensitivity = 0.428, specificity = 0.78, optimal threshold = 5.095, Youden index = 0.208, F1 score = 0.5); DSL showed an relative lower predictive value (AUC = 0.572, sensitivity = 0.246, specificity = 0.893, threshold = 3.975 ms); SCV showed a balanced but modest predictive performance (AUC = 0.615, sensitivity = 0.514, specificity = 0.689); CSA and neural swelling rate both had the highest specificities (0.994 and 0.966, respectively) and comparable AUCs (0.614 and 0.617) with high Youden indices of 0.436 and 0.43, marking them as strong indicators for prognosis (**Table 7**). For the ulnar nerve, DML and DSL offered moderate predic-

Table 6. Univariate and multivariate logistic regression analyses of factors affecting the prognosis of ulnar nerve injuries

Factor	Univariate		Multivariate	
	P	OR (95% CI)	P	OR (95% CI)
DML (ms)	0.002	2.714 (1.463-5.161)	0.015	2.542 (1.199-5.388)
DSL (ns)	0.029	1.352 (1.035-1.778)	0.124	1.290 (0.933-1.785)
SCV (m·s-1)	0.024	0.962 (0.929-0.994)	0.107	0.966 (0.925-1.008)
MCV (m·s-1)	0.026	0.968 (0.939-0.996)	0.065	0.968 (0.935-1.002)
SNAP (uv)	0.029	0.921 (0.854-0.991)	0.075	0.924 (0.846-1.008)
CMAP (mv)	0.029	0.868 (0.763-0.984)	0.219	0.909 (0.780-1.058)
Neural cross-sectional area (cm^2)	0.002	1.063 (1.023-1.108)	0.002	1.077 (1.027-1.130)
Neural swelling rate (%)	0.031	1.804 (1.060-3.109)	0.124	1.513 (0.783-2.923)

DML: Comparison of the distal motor latencies; DSL: distal sensory latencies; SCV: Perceived conduction velocity; MCV: Motion conduction velocity; SNAP: Perceived wave amplitude; CMAP: Composite muscle action potential amplitude.

Table 7. ROC curve analysis of factors in predicting prognosis of median nerve injuries

	Cutoff value	Sensitivities	Specificities	AUC	Youden index	F1 score
DML (ms)	5.095	0.428	0.78	0.6	0.208	0.5
DSL (ms)	3.975	0.246	0.893	0.572	0.139	0.356
SCV (m·s-1)	42.295	0.514	0.689	0.615	0.203	0.41
MCV (m·s-1)	46.455	0.688	0.469	0.583	0.157	0.326
SNAP (uv)	6.355	0.71	0.412	0.578	0.122	0.432
CMAP (mv)	7.835	0.783	0.395	0.592	0.178	0.252
Neural cross-sectional area (cm^2)	14.575	0.442	0.994	0.614	0.436	0.61
Neural swelling rate (%)	2.27	0.362	0.808	0.576	0.17	0.45

DML: Comparison of the distal motor latencies; DSL: distal sensory latencies; SCV: Perceived conduction velocity; MCV: Motion conduction velocity; SNAP: Perceived wave amplitude; CMAP: Composite muscle action potential amplitude.

Table 8. ROC analysis of factors in predicting prognosis of ulnar nerve injuries

	Cutoff value	Sensitivities	Specificities	AUC	Youden index	F1 score
DML (milliseconds)	3.505	0.442	0.757	0.606	0.199	0.504
DSL (milliseconds)	3.145	0.406	0.768	0.59	0.174	0.477
SCV (m·s-1)	43.455	0.558	0.582	0.575	0.14	0.404
MCV (m·s-1)	40.99	0.391	0.768	0.564	0.159	0.469
SNAP (uv)	6.25	0.5	0.65	0.567	0.15	0.429
CMAP (mv)	5.005	0.225	0.932	0.563	0.157	0.522
Neural cross-sectional area (cm^2)	20.905	0.391	0.915	0.583	0.306	0.492
Neural swelling rate (%)	2.27	0.362	0.808	0.576	0.17	0.45

DML: Comparison of the distal motor latencies; DSL: distal sensory latencies; SCV: Perceived conduction velocity; MCV: Motion conduction velocity; SNAP: Perceived wave amplitude; CMAP: Composite muscle action potential amplitude.

tive value, specifically: DML (AUC = 0.606, threshold = 3.505 ms) and DSL (AUC = 0.590, threshold = 3.145 ms). CSA displayed an AUC of 0.583 and a high specificity of 0.915 at a threshold of 20.905 cm^2, accompanied by a fair Youden index of 0.306. Although sensitivities were generally moderate, the high specificities and fair Youden indices support the clinical value of these parameters for prognosis assessment (**Table 8**).

The combined predictive model integrating neurophysiological and ultrasound measurements demonstrated excellent performance, with an AUC of 0.967 (**Figure 7E**). The calibration curve (**Figure 7A**) showed strong agree-

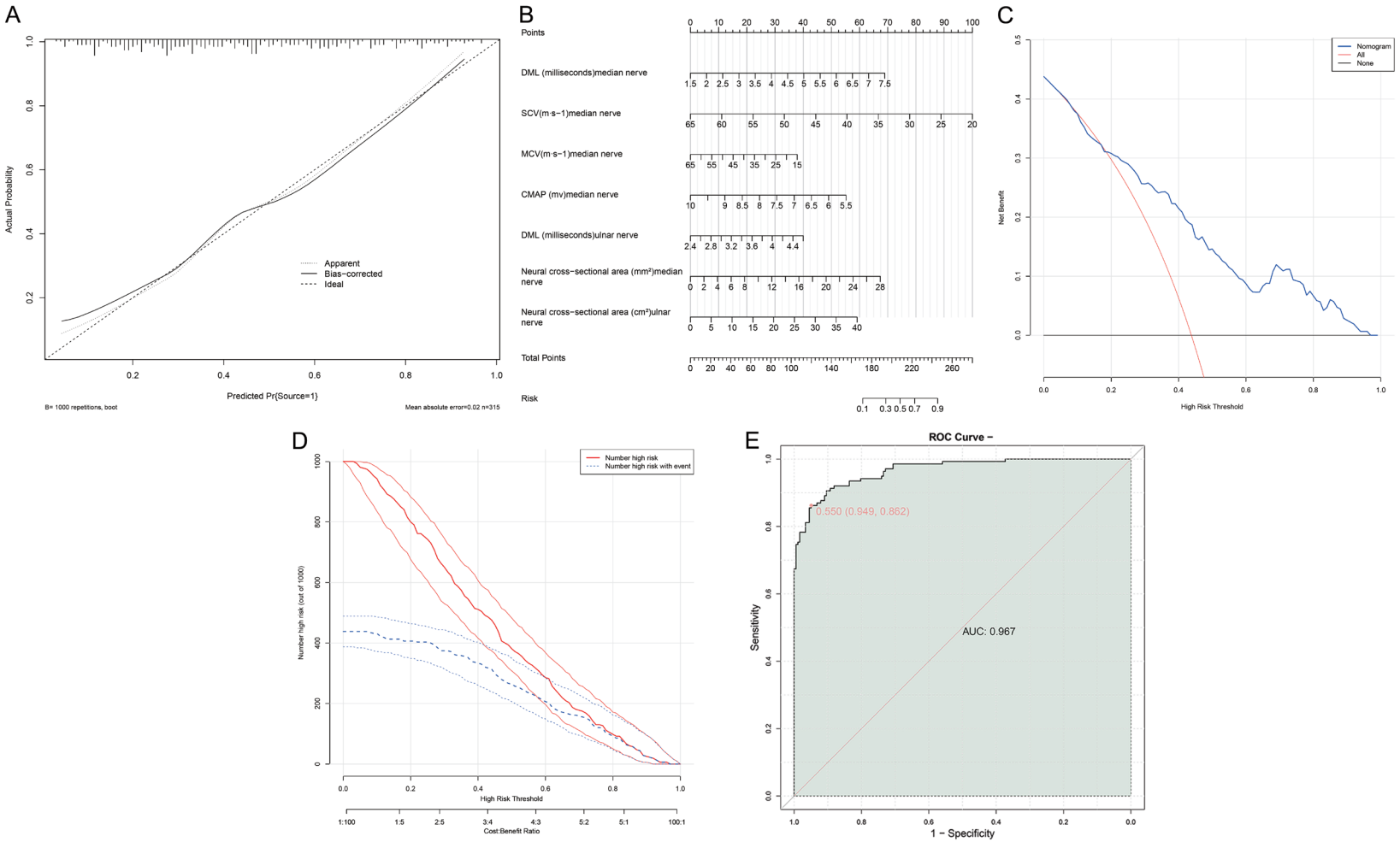

Figure 7. Combined predictive model integrating neurophysiological and ultrasonographic data for evaluating postsurgical functional outcomes and prognosis in patients with median and ulnar nerve injuries. A: Calibration curve; B: Nomogram; C: Decision curve; D: Clinical impact curve (CIC); E: Combined predictive performance.

ment between predicted and observed outcomes, indicating reliable model calibration. A nomogram (**Figure 7B**) was developed to visualize the contribution of each predictor, enabling individualized risk stratification. DCA (**Figure 7C**) revealed higher net clinical benefit across a wide range of threshold probabilities of the combined model compared to alternative strategies. The CIC (**Figure 7D**) validated the clinical applicability of this model for stratification between favorable and adverse outcomes. These findings demonstrate the model's superior capability for forecasting functional restoration in median and ulnar nerve injuries.

Discussion

This study combined neurophysiological assessments and high-frequency ultrasound to assess prognosis following median and ulnar nerve repair. Our data confirm the prognostic value of a multimodal diagnostic approach in predicting regenerative potential and identifying critical determinants of postoperative outcomes in peripheral nerve injury.

Significant intergroup disparities were observed in key neurophysiological indices (DML, DSL, SCV, MCV, SNAP, CMAP) between the good and poor prognosis groups. These metrics serve as critical biomarkers of neural integrity, directly reflecting axonal conduction efficiency. Shorter DML and DSL in the good prognosis group suggest accelerated reinnervation kinetics and enhanced impulse transmission post-repair. Such electrophysiological profiles may result from optimized surgical precision or inherently greater neuroregenerative capacity modulated by genetic and phenotypic factors [21-23].

Previous research supports these observations. Khan et al. demonstrated that distinct classes of sensory neurons retain their proportions even with enhanced axon regeneration post-injury, suggesting that intrinsic cellular heterogeneity may influence recovery trajectories [22]. Wood et al. reported that δ-secretase inhibitors promote motor and sensory axon regeneration, highlighting the role of molecular pathways in shaping postsurgical outcomes [24]. This aligns with our findings, where higher SCV and MCV correlated with improved prognosis, potentially reflecting Schwann-cell mediated remyelination and preservation of axonal continuity.

Elevated SCV and MCV in favorable prognosis group were particularly indicative, as conduction velocity improvements closely correlate with myelination status and axonal integrity of nerves. Accelerated conduction signifies superior preservation or restoration of axonal continuity, validating the efficacy of surgical repair [25, 26]. Furthermore, these findings highlight Schwann-cell mediated remyelination as a pivotal regenerative mechanism, a process often modulated by factors such as surgical timing, procedural accuracy, and postoperative rehabilitation therapies [27, 28].

Our findings are consistent with those of Myhovych & Smolanka, who evaluated the prognostic value of ultrasound and electroneuromyography (ENMG) in compressive neuropathies. While similar trends in SCV and MCV were observed, our study uniquely integrated structural ultrasound measurements (e.g., CSA and swelling rate), which were not extensively evaluated in their study. This integration of functional and structural assessments provides a more comprehensive mechanistic understanding of nerve regeneration [26].

Furthermore, the higher SNAP and CMAP values observed in the good prognosis group corroborate the presence of a more functionally preserved neural environment. These elevated amplitudes indicate better preservation or regeneration of sensory and motor fibers, which may be influenced by factors such as the speed of axonal growth, the neuronal survival, and the balance between pro- and anti-regenerative factors within the nerve microenvironment [29, 30]. These variables might be indirectly modified through pharmacological interventions or physical therapies focused on enhancing neural repair [31].

The pivotal role of Schwann cells in remyelination is further supported by Balakrishnan et al., who emphasized their importance in intraoperative neurophysiological monitoring [32]. Our findings extend this concept by demonstrating that post-surgical Schwann-cell activity, inferred through improved conduction velocities, correlates with long-term functional outcomes. This mechanistic link underscores the therapeutic potential of strategies targeting Schwann-cell function to optimize nerve regeneration.

Ultrasound measurements also offered valuable prognostic insights. Significant intergroup differences in neural CSA and swelling rate signify structural and mechanical aspects of nerve repair that cannot be captured through neurophysiological testing alone. A smaller CSA observed in the good prognosis group likely suggests reduced postoperative edema and more effective initial alignment and coaptation of nerve stumps during the surgery.

Sowah et al. demonstrated the utility of ultrasound in surgical planning for complex nerve injuries with blood vessel damage, emphasizing its role in detecting structural abnormalities [33]. Our study expands on this by showing that ultrasound measurements, particularly swelling rate, can predict recovery when integrated with electrophysiological data. This synergistic, multi-modal diagnostic approach aligns with the “one health” perspective, enhancing translational outcomes [34].

Additionally, the lower neural swelling rates seen in patients with good outcomes may reflect reduced extrinsic compression on the regenerating nerve, attenuated inflammatory responses, or improved microvascular perfusion. These structural signs provide valuable insight into nerve healing milieu. When integrated with neurophysiological data, they yield a more comprehensive understanding of the recovery process [30].

Our correlation and logistic regression analyses demonstrated that both individual findings and their synergistic interactions exerted substantial prognostic influence. The combined predictive model achieved outstanding discriminative accuracy for postoperative recovery trajectories, highlighting the diagnostic value of multimodal integration. This high predictive performance supports the clinical adoption of integrated neurophysiological-ultrasonographic diagnostics to personalize rehabilitation regimens.

The variation in patient outcomes is likely attributable to the interplay of intrinsic factors (e.g., genetic predispositions, demographic characteristics, and pre-existing comorbidities) and extrinsic factors (surgical techniques, postoperative care protocols). These observations reinforce the need for customized surgical and rehabilitative strategies. For example, certain genetic markers may accelerate nerve regeneration, representing a potential area for future research and a potential foundation for precision medicine initiatives [34, 35].

Moreover, the influence of early mobilization and targeted physical therapy should not be underestimated. Rehabilitation protocols designed to optimize neural recovery must be guided by objective functional assessments, enabling targeted interventions that enhance neural plasticity and functional reinnervation. The benefits of early, intensive neurorehabilitation are supported by Gouveia et al., who demonstrated that structured rehabilitation programs improve functional outcomes in traumatic nerve injuries [36]. Our study complements these findings by providing a framework for tailoring rehabilitation strategies through the integration of neurophysiological and ultrasonographic metrics.

Our investigation offers significant insights into postoperative recovery and prognosis following surgical repair of median and ulnar nerve injuries. Nevertheless, several limitations warrant consideration. First, the relatively small sample size may limit the generalizability of our findings to broader populations. Second, the observational and retrospective design introduces potential selection biases and precludes establishing causal relationships. Third, variability in surgical techniques and postoperative care among patients may have influenced outcomes. Fourth, although advanced diagnostic tools were employed, both ultrasound and neurophysiological measurements have inherent technical limitations. Ultrasound image resolution may be suboptimal, and electrophysiological data can be sensitive to testing conditions. Future studies should include larger, multicenter cohorts with standardized surgical, rehabilitation, and assessment protocols to improve reproducibility and external validity.

Conclusion

Integration of neurophysiological and ultrasonographic assessments provides a more comprehensive and accurate predictor of postoperative recovery in patients with median and ulnar nerve injuries. Further investigations should extend beyond functional and structural evaluation to include molecular and genetic profiling, which may further refine prognostic

accuracy and uncover novel therapeutic targets. Potential directions include pharmacogenomic strategies to enhance nerve repair and the development of new biomaterials to improve surgical outcome.

A multidisciplinary, integrative approach - encompassing neurophysiology, imaging, molecular biology, and regenerative medicine - holds promise for advancing nerve injury treatment and refining individualized patient care.

Disclosure of conflict of interest

None.

Address correspondence to: Yu Yuan, Department of Ultrasound, Tianjin Hospital, No. 406 Jiefang Nan Lu, Hexi District, Tianjin 300211, China. E-mail: tianjinyyjdt@163.com

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