Retrospective Cohort Study

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Assessment of simulation training efficacy in improving microsurgical skills: a retrospective analysis

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Background: Microsurgery demands an intensive period of skill acquisition due to its inherent complexity. The development and implementation of innovative training methods are essential for enhancing microsurgical outcomes. This study aimed to evaluate the impact of a simulation training program on the clinical results of fingertip replantation surgeries.

Materials and methods: A total of 276 replanted digits from 232 patients were included in this study, with a follow-up period of 6 months. Surgeons were identified and divided into trained and control groups, with the trained group receiving the rat tail training program. Primary outcomes included survival rates, replantation duration for each fingertip, degrees of flexion, Semmes–Weinstein monofilament test results, static two-point discrimination scores, Michigan Hand Questionnaire (MHQ) scores, and the incidence rates of complications such as arterial insufficiency and pulp atrophy.

Results: Out of 1191 patients screened, 232 met the criteria for analysis. The average patient age was 41.3 years, predominantly male (87.1%). Trained microsurgeons performing Zone 1A replantation had higher success rates, shorter surgery durations, and fewer arterial complications compared to their untrained counterparts. For Zone 1B, they also showed improved operation times, decreased venous congestion and pulp atrophy, and better sensation outcomes. The results of trained group remained consistent across both single and multiple replantation, while the control group's outcomes varied in multiple replantation with less favorable results. The trained group reported better scores on the MHQ at 6-month follow-ups, particularly regarding work performance, pain levels, aesthetics, and satisfaction.

Conclusions: The simulation training program using a rat tail model has proven effective in enhancing the skills necessary for improved fingertip replantation. Participants in the program performed surgeries more efficiently and achieved better clinical outcomes. The structure of the training has demonstrated benefits, which may lead to improvements in various microsurgical procedures, positively impacting trainee surgeons, patient care, and the broader medical community.

Keywords: finger replantation, medical education, microsurgery, simulation training

Introduction

Fingertips are essential for both functional engagement in daily activities and psychological well-being, serving as vital components of the upper extremities. Despite their importance, fingertips are particularly susceptible to injury, with the rise of industrialization contributing to an increased incidence of finger amputations, currently estimated at 7.5 per 100 000 person-years in the United States[1]. Fingertip amputations are a prevalent and critical concern in hand injuries, accounting for about 35% of cases, with the index and middle fingers being the most commonly affected[2]. In developing countries, the loss of fingertips can be devastating for people who rely heavily on professions in manufacturing and handicrafts. Therefore, despite the procedural complexities, fingertip replantation is the most preferred treatment to restore function and aesthetics in these critical cases.

The realm of hand surgery underwent a paradigm shift in 1968 when Komatsu and Tamai reported the first successful thumb replantation[3]. Around the same time, Dr. Chen Zhongwei from our institution achieved the unprecedented replantation of a completely severed forearm[4]. These historical successes have led to the restoration of millions of fingers since, with the techniques for replantation undergoing rigorous refinement. Nevertheless, the increasing demand for microsurgeons, who require extensive training and possess specialized skill sets, poses challenges in expanding microsurgical teams and advancing hand surgery practices. Fingertip replantation surgery is not only vital for restoring functionality but also presents significant challenges due to its complexity. Microsurgery techniques involve intricate procedures that necessitate a high level of precision and skill, including vascular anastomosis, nerve repair, and meticulous tissue handling.

The success rates of these surgeries are influenced by various factors such as surgeon experience, time to surgery, and patient-specific characteristics[2]. Moreover, the expertise of surgeons in microsurgery directly correlates with patient outcomes; trained microsurgeons demonstrate superior skills that

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lead to higher survival rates and better functional recovery. To improve clinical outcomes in fingertip replantation surgeries, several measures can be implemented. Structured training programs focused on microsurgical techniques have been shown to significantly enhance surgeon proficiency. The use of practice simulations–such as animal models like rat tails–provides a safe environment for trainees to develop their skills without risking patient safety. These simulations allow for repetitive practice and mastery of complex techniques essential for successful fingertip replantation.

In this study, we investigate the effectiveness of our established microsurgery training program on finger replantation, aiming to illuminate potential improvements in the training and education of future microsurgeons to enhance clinical outcomes. Through rigorous training that emphasizes gradual learning and practical experience, we seek to empower microsurgeons to better serve their patient populations while addressing the pressing need for skilled practitioners in this field.

Methods

Study design

This study was designed as a retrospective analysis of patients who underwent complete fingertip amputation and subsequent replantation at hospital between September 2020 and December 2022. Ethical approval was granted by the Ethics Committee. The work has been reported in line with the STROCSS criteria[5].

The surgeons in the study had completed standardized surgical training and had mastered the principles of sterility, basic surgical operations; however, they had not participated in formal microsurgery skills training and had not yet entered the field of microsurgery. Surgeons at these similar stages were identified and divided into two cohorts: trained group and control group. The trained group received additional instruction through the rat tail training program, whereas the control group did not.

Fingertip amputation was defined as the separation of the finger distal to the insertion of the extensor and flexor tendons, occurring on either the distal phalanx or proximal phalanx of the thumb. The classification of amputation levels followed Sebastin and Chung's system, distinguishing between Zone 1A and Zone 1B injuries[6]. Zone 1A was defined as the area from the distal part to the lunula, including the sterile matrix, while Zone 1B spans the area between the lunula and the root of the nail bed, covering the germinal matrix. Wound types were categorized using Yamano's classification in the severed digits[7]. In knife blade amputations, the tissue is intact, eliminating the need for debridement or bone shortening. Saw amputations result in crushed tissue ends, requiring debridement before replantation. Crushed damage occurs when the fingertip is completely smashed and amputated.

Inclusion and exclusion criteria

Inclusion criteria of patients necessitated the presence of a viable amputated fragment with repairable vessels and ischemia times not exceeding 8 hours at room temperature or 24 hours at 4°C. Exclusion criteria included patients who opted out or were unable to consent, those with concurrent upper limb injuries, documented atherosclerosis, Raynaud's syndrome, coagulopathies, or prior hand surgeries within 1 year preceding the study. Patients with avulsion amputation were also excluded due to the ambiguity of the damaged region and increased surgical complexity.

Animal training program

Our hospital is the National Orthopedic Medical Center of China, an educational institution that trains professional orthopedic doctors. Experts of our replantation center participated in the development of a training program, aiming to improve the microsurgical skills of residents and general surgeons entering hand surgery specialties. This training program included the essential skills for fingertip amputation, such as two-handed coordination, visual adaptation, precise positioning, delicate tissue dissection, and suturing under a microscope, emphasizing the importance of categorization and repetitive practice.

The training program provided participants with comprehensive hands-on experience in microsurgical techniques using microscope, covering critical tasks such as vessel identification, exposure, delicate tissue dissection, and end-to-end anastomosis performed on rat tail vessels. In addition, trainees received training in skills such as the preparation and maintenance of the surgical site, as well as vessel handling. All exercises were conducted under the supervision of experienced microsurgeons.

The training format and anatomical diagram of the rat tail are shown in Fig. 1. Training started with larger vessels at the proximal end of the rat tail and moved toward the finer vessels at the distal end. To improve their capability in managing suture tension, selecting suitable suture sizes, and placing stitches with precision during vascular anastomosis. Each participant engaged in 2-hour training sessions, held twice weekly for 1 month before their clinical operations. This comprehensive training totaled 16 hours of training.

Operative and postoperative management

All surgeries were performed by microsurgeons involved in the study and were supervised by superior doctors. Fingertip replantation required the administration of brachial plexus anesthesia and the application of a tourniquet to control blood flow. The initial steps of the procedure involved carefully removing any damaged tissue through debridement and shortening the bone if it was excessively long or irregular. To ensure stability of the distal phalanx, one or two longitudinal intramedullary Kirschner wires were inserted. The decision on the number of wires used depended on the quality and quantity of the remaining bone stock, ensuring adequate fixation for optimal healing. Routine nail plate removal was performed if there was damage to the nail plant or venous drainage issues. Number of repaired veins and nerves, and time of replantation were recorded by the superior doctors.

Each fingertip required one arterial anastomosis, and venous anastomosis was executed according to the anatomical zone characteristics. Nerve repairs were done with epineural sutures if possible, and nail bed repairs were conducted. While, this study did not address repairs to tendon damage. Because according to the anatomical division of Sebastin and Chung's, the location of the broken end is usually outside the distal end of the ligament insertion point.

After surgery, patients received heparin and papaverine for 3–5 days to prevent blood clots and spasms. In addition, all

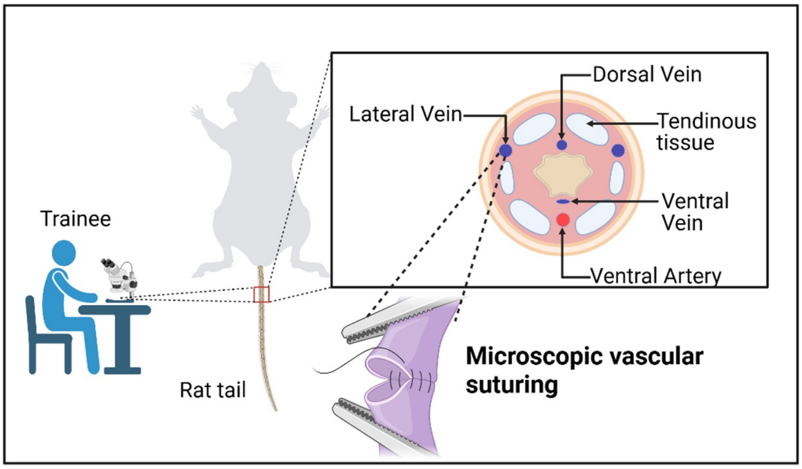

Figure 1. Schematic diagram of rat tail training model. The tail of the rat has longitudinal tendinous tissue, and the lateral veins are located superficially between two tendinous tissues. Trainees need to find these veins through a microscope and practice suturing.

patients were required to stop smoking to enhance the chances of healing.

Clinical outcomes

Clinical outcomes were evaluated based on early and late complication incidence rates, as well as measurements of motion and tactile sense. Early complications after surgery mainly included arterial insufficiency and venous congestion. Late complications were wound nonunion, infection, neuroma, persistent pain, cold intolerance, and pulp atrophy. To assess the functional outcomes, we evaluated the degree of active flexion at the distal interphalangeal joint (DIJP) (or interphalangeal joint in thumbs), conducted the Semmes–Weinstein monofilament test, and estimated static two-point discrimination. In the Semmes–Weinstein monofilament test, if a patient could feel a monofilament marked 4.56 (4.0 g) or lighter, it indicated they had kept their protective sensation of touch. These functional assessments were conducted 6 months after the initial replantation. Brief Michigan hand outcomes questionnaire (MHQ) was used to assess patients report outcomes. The questionnaire features 12 items rated on a 1–5 Likert scale, focusing on various aspects of hand functionality such as pain, sensation, and the ability to perform daily tasks. Responses are scored to create a summary score ranging from 0 to 100, with higher scores indicating better functioning and satisfaction. Static two-point discrimination was determined by placing two points of a caliper longitudinally against the skin until blanching occurred and by then asking the patient whether he or she feels one or two points. The smallest distance in which two of three attempts were correctly identified is recorded in millimeters.

Data analysis

Participants' demographic characteristics and surgical details were provided as descriptive statistics. Clinical outcomes were extracted from hospital's medical record data. The study focused on the differences between the trained group and the control group, taking into account the level of amputation and the number of fingertips amputated. Patients with replantation on two or more fingertips were grouped separately from those with a single fingertip replanted. Data were reported as mean (standard deviation [SD]), median (interquartile range), and 95% confidence intervals (CIs). Ratio difference (RD) was employed to analyze incidence rates of complication in different groups. Continuous variables were assessed using the Wilcoxon–Mann–Whitney test and the Welch *t*-test, and categorical variables were evaluated by the χ^2 test. We considered *P*-values of less than 0.05 to be statistically significant, and estimates were made using 95% CIs. Statistical analyses were performed using SPSS software, version 25.

Results

Of 1191 patients underwent finger replantation surgeries at our medical center, 232 patients met the criteria (Fig. 2). Mean age was 41.3 years, with an SD of 10.0 years, and 87.1% were male. Table 1 provides detailed information about the demographics. There are no significant differences were observed between the two groups in any demographic variables.

We analyzed fingertip amputations using Sebastin and Chung's classification (Table 2). In the case of Zone 1A replantation, individuals in the trained group exhibited higher survival rates and fewer complications. Trained microsurgeons accomplished replantation in less time, and the trained group saw a lower rate of arterial insufficiency, compared with the control group (9 [10.2%] vs. 16 [23.2%], $P = 0.028$, RD [CIs]: –25.1%, 1.3%). Incidence rates of venous congestion, cold intolerance, pulp atrophy, persistent pain, and neuroma did not differ significantly between the groups ($P > 0.05$). The trained group maintained protective sensation in 65.9% of replanted digits, compared to 53.6% in the control group ($P = 0.162$), with RD (CIs) from –3.0% to 27.0%. The mean static two-point discrimination values were 7.98 (2.48) mm for the trained group and 8.47 (2.68) mm for the control group ($P = 0.34$). The active flexion of the DIPJ (interphalangeal joint in thumbs) was 62.3 (3.43) and 60.7 (4.86) degrees in the trained and control groups respectively ($P = 0.083$).

In Zone 1B, trained microsurgeons completed procedures significantly faster, averaging 124.1 (6.9) min compared to 147.0 (12.3) min in the control group ($P < 0.01$), with mean

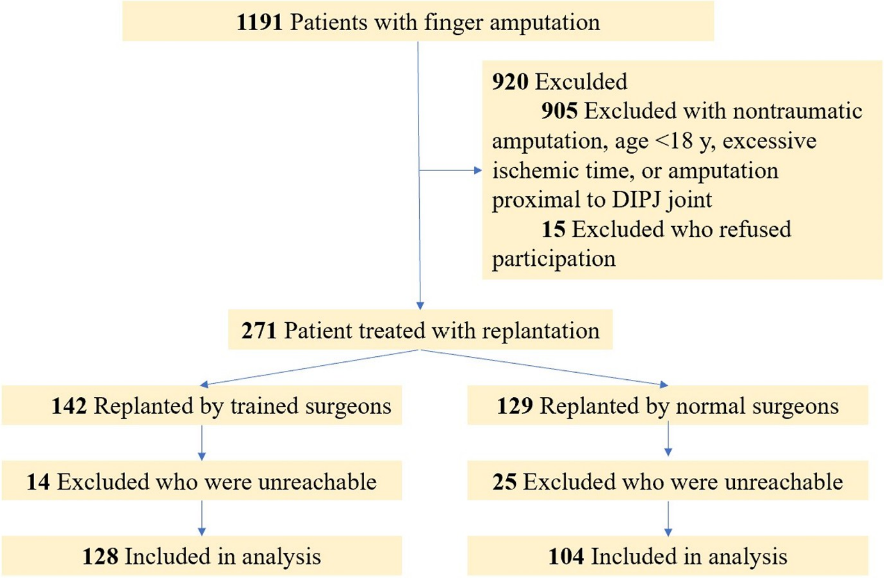

Figure 2. Study enrollment. DIPJ, the distal interphalangeal joint (interphalangeal joint in thumbs).

difference (CIs) from −35.4 to −29.1 min. The trained group experienced markedly lower rates of venous congestion (reduction from 31.8% to −2.7%, *P* = 0.019) and pulp atrophy (RD [CIs]: 34.7% to −4.2%, *P* = 0.012), highlighting their superior skills in tissue handling and vascular connection honed through animal model training. This training likely helped them avoid excessive dissection during surgery. Moreover, 83.1% of patients in the trained group retained protective sensation post-operation, significantly higher than the 64.8% in the control group (*P* = 0.038). Sensory outcomes, measured by static two-point discrimination, were better in the trained group with mean (SD) of 6.64 (2.12) versus 9.19 (3.49) mm in the control group (*P* = 0.030). These sensory differences were linked to the higher rates of vein and nerve repairs achieved by the trained microsurgeons, leading to enhanced sensory recovery in patients. These findings suggested that through rigorous training, microsurgeons had mastered the precise identification of tissues and had developed proficient microsurgical techniques. This expertise enabled them to perform more effective replantation, particularly in delicate tasks such as vessel and nerve anastomosis, and in preserving tissue integrity.

Table 1

Demographics of the participants

	Trained group	Control group	*P* value
Patient, no.	128	104	
Age, mean (SD), year	40.8 (10.51)	41.9 (9.56)	0.298
Ischemia time, mean (SD), hour	6.5 (2.88)	6.0 (2.98)	0.693
Sex, no. (%)			0.325
Male	110 (85.9)	92 (88.5)	
Female	18 (14.1)	12 (11.5)	
Smoking, no. (%)			0.704
Yes	77 (60.2)	60 (57.7)	
No	51 (39.8)	44 (42.3)	
Cause of injury, no. (%)			0.924
Knife blade	72 (56.2)	60 (57.7)	
Saw	43 (33.6)	35 (33.7)	
Crush	13 (10.2)	9 (8.7)	
Traumatic amputation location, no. (%)			0.984
Thumb	30 (19.6)	23 (18.7)	
Index finger	49 (32.0)	40 (32.5)	
Middle finger	45 (29.4)	39 (31.7)	
Ring finger	27 (17.6)	20 (16.3)	
Small finger	2 (1.3)	1 (0.8)	
Pattern of amputation, no. (%)			0.685
Single fingertip	106 (82.8)	86 (82.7)	
Two fingertips	19 (14.8)	17 (16.3)	
Three fingertips	3 (2.3)	1 (1.0)	
Sebastian's classification, no. of digits (%)			0.813
Zone 1A	88 (57.5)	69 (56.1)	
Zone 1B	65 (42.5)	54 (43.9)	

Multiple fingertip replantation is a draining and physically and mentally demanding surgery, usually representing the most difficult surgery in hand surgery. In the stratified analysis, we compared outcomes between groups handling multiple fingertip replantation: 22 patients with 47 digits in the trained group and 18 patients with 37 digits in the control group. The trained group maintained consistent survival rates, operative times, and complication rates regardless of whether a single or multiple fingertips were replanted. The control group showed significant variability. The control group had long surgery durations on average (151.4 [14.9] vs. 132.7 [12.4] min, *P* < 0.001, mean difference [CIs]: −23.8, −13.6 min), a reduced rate of successful replantation (54.1% vs. 75.6%; *P* = 0.018), and a higher incidence of arterial insufficiency (10.5% vs. 48.6%, *P* < 0.001, RD [CIs]: 20.9%, 54.4%), venous congestion (18.6% vs. 40.5%, *P* = 0.010, RD [CIs]: 4.9%, 19.3%), and pulp atrophy (25.6% vs. 51.4%, *P* = 0.005, RD [CIs]: 7.3%, 43.0%) in cases of multiple fingertips replantation. Increases were also observed in other complications, as outlined in Table 3. These results indicated that trained microsurgeons performed better overall,

Table 2

Operative information and postoperative results of patients treated with replantation classified by Chung's classification

	Zone 1A				Zone 1B			
	Trained group	Control group	*P* value	Ratio difference (95% CI)	Trained group	Control group	*P* value	Ratio difference (95%CI)
Digits, no.	88	69			65	54		
Repair vein, no. of digits, number (%)			0.319				0.002[a]	
None	79 (89.8)	65 (94.2)	-	(−13.2%, 5.0%)	1 (1.5)	2 (3.7)	-	(−11.1%, 5.0%)
One	9 (10.2)	4 (5.8)	-	(−5.0%, 13.2%)	13 (20)	21 (38.9)	-	(−34.4%, −2.5%)
Two and more	0 (0)	0 (0)	-	-	51 (78.5)	31 (57.4)	-	(4.3%, 36.7%)
Repair nerve, no. of digits, number (%)			0.076				0.002[a]	
None	77 (78.5)	66 (95.7)	-	(−17.1%, 1.2%)	2 (3.1)	2 (3.7)	-	(−9.7%, 7.3%)
One	11 (12.5)	3 (4.3)	-	(−1.2%, 17.1%)	4 (6.2)	16 (29.6)	-	(−37.2%, −9.9%)
Two	0 (0)	0 (0)	-		59 (90.8)	36 (66.7)	-	(13.1%, 41.0%)
Time of replanting each finger, mean (SD), min	94.2 (6.5)	126.5 (11.9)	<0.01[a]	(−35.4, −29.1)[b]	124.1 (6.9)	147.0 (12.3)	<0.01[a]	(−26.6, −19.1)[b]
Survival rate (%) (no. of digits)	81.8 (72)	66.7 (46)	0.029[a]	(1.5%, 28.7%)	87.7 (57)	72.2 (39)	0.033[a]	(1.1%, 29.9%)
Complication, no. of digits, rate (%)								
Arterial insufficiency	9 (10.2)	16 (23.2)	0.028[a]	(−25.1%, 1.3%)	7 (10.8)	11 (20.4)	0.146	(−23.3%, 3.5%)
Venous congestion	20 (22.7)	15 (21.7)	0.883	(−12.4%, 13.7%)	8 (12.3)	16 (29.6)	0.019[a]	(−31.8%, 2.7%)
Cold intolerance	21 (23.9)	22 (31.9)	0.263	(−22.0%, 5.9%)	12 (18.5)	14 (25.9)	0.327	(−22.5%, 7.3%)
Pulp atrophy	22 (25.0)	22 (31.9)	0.340	(−21.0%, 7.1%)	10 (15.4)	19 (35.2)	0.012[a]	(−34.7%, 4.2%)
Pain	3 (3.4)	1 (1.4)	0.792	(−4.7%, 8.2%)	1 (1.5)	6 (11.1)	0.069	(−20.7%, 0.7%)
Neuroma	2 (2.3)	1 (1.4)	1.000	(−5.7%, 6.6%)	1 (1.5)	3 (5.6)	0.484	(−13.7%, 3.6%)
Functional outcome								
Monofilament test, no. of digits, number (%)								
Remain protective sensation	58 (65.9)	37 (53.6)	0.162	(−3.0%, 27.0%)	54 (83.1)	35 (64.8)	0.038[a]	(2.5%, 33.4%)
Static two-point discrimination (mm)								
Mean (SD)	7.98 (2.48)	8.47 (2.68)	0.340	-	6.64 (2.12)	9.19 (3.49)	0.030[a]	-
Median, [IQR]	8[6–9]	8.5[6–10]	-	-	6[5–8]	8.5[7–11]	-	-
Active flexion of DIPJ								
Mean (SD)	62.3° (3.43)	60.7° (4.86)	0.083	-	57.4° (4.99)	58.4° (6.16)	0.484	-
Median, [IQR]	62, [61–64]	57, [53–58]	-	-	62, [53–60]	57, [54–61]	-	-

[a] Statistically significant at $P < 0.05$.

[b] Mean difference (95% CI). Continuous variables were assessed using the Wilcoxon–Mann–Whitney test and the Welch *t*-test, and categorical variables were evaluated by the χ^2 test.

especially when dealing with the complexities of multiple fingertip replantation. From better clinical outcomes and more stable surgical performance, this training improved not only technical skills but also significant psychological resilience and advanced surgical proficiency.

Patient-reported outcomes were assessed using the MHQ at 6 months after the surgery (Table 4). Patients treated by trained microsurgeons reported a notably higher total MHQ score compared to the control group (84.6 [15.5] vs. 77.0 [22.7], $P < 0.001$). The trained group reported improved outcomes particularly in work performance (84.1 [14.1] vs. 72.6 [21.5], $P < 0.001$), pain management (93.0 [15.9] vs. 81.0 [25.4], $P < 0.001$), aesthetics (79.0 [15.6] vs. 71.4 [24.7], $P = 0.002$), and satisfaction (78.2 [12.1] vs. 71.8 [18.6], $P = 0.042$). Overall, microsurgeons in the trained group demonstrated improved skills in replantation surgery, evident in vascular anastomosis, a higher survival rate, reduced operation duration, a lower incidence of arterial insufficiency and higher patient-reported outcomes attributed to the animal training program.

Discussion

This study aimed to assess the effectiveness of a training program by comparing the outcomes of fingertip amputation replantation. The results demonstrated that the trained group experienced shorter surgery times, fewer complications, and better sensory outcomes, highlighting the program's value for both novice microsurgeons and their patients. Usami *et al*[8] reported that microsurgeons with experience in over 51 digital replantation operations maintained a higher success rate (86.4%) compared to those with fewer than 50 replantation operations (74.2%). Yoon *et al*[9] suggested that operative proficiency accounted for 17% of the estimated success of digit replantation and revascularization. Our study supports the idea that training with animal models improves trainees' skills, leading to better surgical outcomes.

Studies have shown that fingers with properly restored venous drainage have higher survival rates[6,10,11]. The success of these repairs depends largely on the surgeon's expertise and their precision in tissue identification under the time constraints of the surgery[9]. However, vein repair, especially in Zone 1B, is challenging due to the thinness of the vein walls and their small diameter, often measuring under 0.6 mm, which becomes even more daunting in Zone 1A[12]. Within the microscopic field of view, the recognition of these tiny structures largely relies on empirical indicators, such as location, texture, and color, which are challenging to articulate through verbal descriptions alone.

Table 3

Outcomes and complications between trained group and control group

	Trained group				Control group			
Outcomes	**Single fingertip replantation**	**Multiple fingertips replantation**	***P* value**	**Ratio difference (95% CI)**	**Single fingertip replantation**	**Multiple fingertips replantation**	***P* value**	**Ratio difference (95% CI)**
No. of digits	106	47	-	-	86	37	-	-
Survival rate (%) (no. of digits)	84.9 (90)	83.0 (39)	0.762	(−9.5%, 16.2%)	75.6 (65)	54.1 (20)	0.018[a]	(3.6%, 39.1%)
Time of replanting each finger, mean (SD), min	104.8 (16.6)	109.4 (13.4)	0.092	(−10.1, 0.8)[b]	132.7 (12.4)	151.4 (14.9)	<0.001[a]	(−23.8, −13.6)[b]
Complication no. of digits, number (%)								
Arterial insufficiency	10 (9.4)	6 (12.8)	0.738	(−16.4%, 6.5%)	9 (10.5)	18 (48.6)	<0.001[a]	(−54.4%, −20.9%)
Venous congestion	16 (15.1)	12 (25.5)	0.123	(−25.5%, 2.6%)	16 (18.6)	15 (40.5)	0.010[a]	(−19.3%, −4.9%)
Cold intolerance	22 (20.8)	11 (23.4)	0.713	(−18.0%, 10.4%)	22 (25.6)	14 (37.8)	0.171	(−30.2%, 4.8%)
Pulp atrophy	20 (18.9)	12 (25.5)	0.350	(−22.0%, 6.7%)	22 (25.6)	19 (51.4)	0.005[a]	(−43.0%, −7.3%)
Pain	1 (0.9)	3 (6.4)	0.163	(−15.3%, 0.5%)	2 (2.3)	5 (13.5)	0.042[a]	(−25.8%, −1.7%)
Neuroma	1 (0.9)	2 (4.3)	0.553	(−13.3%, 1.9%)	1 (1.2)	3 (8.1)	0.081	(−20.2%, 0.4%)

[a] Statistically significant at $P < 0.05$.

[b] Mean difference (95% CI).

As a result, microsurgeons require comprehensive training in tissue recognition, a vital skill for fingertip replantation.

In our study, we found that a higher proportion of nerve repair in the trained group correlated with improved sensory recovery during a 6-month follow-up period. However, there is ongoing debate about the necessity of nerve repair in fingertip replantation surgeries. Some experts believe that nerve repair may not be essential due to the short distance in fingertips and the nerves are primarily sensory[13]. Hayashi *et al* reported that sensory outcomes after fingertip replantation were not significantly affected by nerve repair[6,14]. Conversely, Usami *et al*[8] highlighted nerve repair as an important indicator in successful distal digit replantation. They suggested that because digital nerves have a rich supply of blood vessels, a vascular network may develop at the site of nerve repair. This could lead to rapid neovascularization in the distal stump and potentially stabilizing blood circulation, thereby enhancing the survival rate at the distal level.

In microvascular training, the rat femoral vessel model has been widely used for teaching techniques such as vessel anastomosis, grafting, and flap procedures[15,16]. The diameters of the rat femoral artery and vein are approximately 1 and 2 mm, respectively[17], and they are favored due to their consistent anatomical locations. However, these vessels lack the challenging size and length that trainees need for more advanced practice. Therefore, the rat tail vessel model was considered as a more suitable option. This model contains one artery and three veins along its long axis: one ventral artery, one dorsal vein, and two lateral caudal veins. The lateral caudal veins are particularly useful due to their accessibility for training with minimal invasiveness. These veins vary in diameter from 1.0 to 0.25 mm[16], allowing for repeated and progressively challenging training sessions. It also helps in developing dexterity with microscopes and microsurgical instruments.

Table 4

Brief MHQ score of affected side at 6 months after replantation

BMHQ Score	Trained group	Control group	*P* value
Mean (SD)			
Total score	84.6 (15.5)	77.0 (22.7)	<0.001[a]
Overall function	84.2 (17.2)	76.8 (20.5)	0.026
ADLs[b]	89.3 (12.1)	88.5 (19.1)	0.206
Work performance	84.1 (14.1)	72.6 (21.5)	<0.001[a]
Pain	93.0 (15.9)	81.0 (25.4)	<0.001[a]
Aesthetics	79.0 (15.6)	71.4 (24.7)	0.002[a]
Satisfaction	78.2 (12.1)	71.8 (18.6)	0.042[a]

[a] Statistically significant at $P < 0.05$.

[b] Activities of daily living.

Surgeons often seek to improve their medical skills through direct involvement in complex surgical procedures, which may risk patient safety[18]. This practice creates a significant psychological strain for young doctors[19]. Previous surveys have shown that medical residents frequently feel unprepared to perform procedures on their own and fear causing harm to patients[20]. Traditional, passive educational approaches, such as lecture lectures, fell short in equipping them with the necessary practical skills[21]. The rat tail model facilitated hands-on learning without endangering patients. It provided a low-risk setting for trainees to apply microsurgical principles confidently, thus reducing their stress. This approach resolved the conflict between the educational requirements of young surgeons and the patients' preference for experienced care, avoiding ethical issues[22]. In addition, integrating practical courses at appropriate time intervals was in line with a typical clinical schedule, with two classes per week lasting for a month, for a total of 16 hours, which was an acceptable course arrangement for clinical doctors. Periodic course arrangements also encouraged spaced repetition—a strategy proven to improve memory retention and skill acquisition[23–26]. Given the development of ChatGPT in the medical and veterinary field, further improvements may be made through artificial intelligence models such as ChatGPT for assisted learning[27–30].

Multiple finger amputations, while less common in fingertip injuries, occur more frequently in hand injuries. Recent studies recommend replantation over revision amputation for multiple amputations. Chung *et al*[31] suggested that if it is technically feasible, replantation, especially for three or more amputated fingers can result in better patient-reported outcomes and long-term benefits. Our training program's success suggested potential benefits for both single and multiple amputations across all types of finger injuries. This is particularly pertinent in developing countries, where many people work in manual labor and are at a higher risk for finger amputations due to agricultural machinery, metal tools, and bladed hand tools[32]. In developed countries, this training program can address the vicious cycle of insufficient practice in distal replantation among microsurgeons. The lack of opportunities to perform enough procedures can lead to decreased experience, a higher failure rate, and a hesitancy to attempt these surgeries[2,33,34]. Implementing this training program can empower microsurgeons to better serve their patient populations.

Although the training program had been implemented for a period of time, we noticed the clinical outcomes can be affected by many confounding variables. In this study, we did not collect the potential influence factors such as time intervals after training, mental and physical state of microsurgeons. Confounding factors such as smoking history of patients, working years of trainees were not considered as stratification. Furthermore, the stratified analysis results of multiple fingertips replantation were still limited by inadequate statistical power due to the rarity of amputation patterns and only one follow-up time point (6 months after replantation) was taken. In the end, prospective studies are still needed to elucidate the specific benefits of this training program in the future.

Conclusions

Our evaluation confirmed that the rat tail model was an effective tool for enhancing microsurgical skills, particularly for fingertip replantation procedures. Microsurgeons trained through this program have shown shorter operation times and superior clinical outcomes. The success of this training can be linked to its focus on developing trainees "microsurgical skills using a structured regimen that emphasizes gradual, repetitive, and spaced learning. This method also increased the trainees" self-confidence by providing a realistic, low-risk, practice setting. We suggested the use of this training extends beyond fingertip replantation, potentially benefiting young surgeons, patients, healthcare systems, and various medical specialties worldwide.

Ethical approval

Ethical approval was granted by the Ethics Committee of Shanghai Sixth People's Hospital, affiliated with Shanghai Jiao Tong University School of Medicine (Approval No. 2020-145).

Consent

Written informed consent was obtained from the patient for publication of this case report and accompanying images. A copy of the written consent is available for review by the Editor-in-Chief of this journal on request.

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Author's contribution

H.Y. had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. Conceptualization, funding acquisition, project administration: H.Y. Data curation, investigation: all authors. Writing – original draft: X.H., T.G., Y.C. Formal analysis: X.H., E.L., project administration: H.Y., Z.Z., writing – review & editing: H.Y., E.L.

Conflicts of interest disclosure

All the authors declare to have no conflicts of interest relevant to this study.

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Data are available upon reasonable request.

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