Am J Transl Res 2024;16(5):1798-1805
www.ajtr.org /ISSN:1943-8141/AJTR0154549

Original Article

Integrating digital design with 3D printing technology achieves customized and precise approaches for flap transplantation to facilitate fingertip defect surgery

Hui Lu[1,2,3*], Shuo Han[1,2*], Rong Liu[3,4#], Xuexiao Ma[1#]

[1]Department of Spinal Surgery, The Affiliated Hospital of Qingdao University, Qingdao, Shandong, China; [2]Department of Medicine, Qingdao University, Qingdao, Shandong, China; [3]Institute of Medical Innovation and Transformation, Puren Hospital Affiliated to Wuhan University of Science and Technology, Wuhan, Hubei, China; [4]Department of Orthopedics, Puren Hospital Affiliated to Wuhan University of Science and Technology, Wuhan, Hubei, China. [*]Equal contributors and co-first authors. [#]Equal contributors and co-corresponding authors.

Received November 21, 2023; Accepted April 8, 2024; Epub May 15, 2024; Published May 30, 2024

Abstract: Objective: This study investigates the clinical efficacy of integrating digital design with three-dimension (3D) printing technology in the transplantation of flaps for fingertip defects. Methods: A retrospective analysis was conducted from October 2019 to June 2021 on 90 cases of patients with fingertip defects. These included 45 cases in which digital design, coupled with 3D printing, assisted the operation (3D printing group), and another 45 cases where patients underwent traditional pedicle flap transplantation and skin grafting (traditional operation group). A six-month postoperative follow-up assessed various measurements between the two groups, comparing the skin flap survival rate, aesthetic outcome, cold intolerance, sensory recovery, and overall skin flap performance. Results: ① Statistical analysis utilizing the independent samples t-test revealed a significant reduction in both operation time and flap anastomosis rate for the 3D printing group compared to the traditional operation group ($P < 0.05$). ② Conversely, the survival rate, aesthetic outcome, and cold intolerance showed no significant disparities between the groups ($P > 0.05$). ③ Further, the Mann-Whitney U test indicated no significant difference in sensory recovery and overall efficacy assessment between the two cohorts ($P > 0.05$). Conclusion: Integrating digital design with 3D printing technology facilitated the surgical management of fingertip defects, achieving customized and precise approaches in flap transplantation. This precision in personalized skin flap design contributed to reduced operative time and enhanced surgical efficiency in such procedures.

Keywords: Digital design, 3D printing, fingertip defect, skin flap transplantation, three-dimensional reconstruction

Introduction

Fingertip defects constitute some of the most prevalent hand injuries, leading to diminished sensation, overall hand functionality, and a consequent reduction in quality of life [1]. Empirical evidence from clinical practices underscores the advantages of prompt surgical intervention for wound closure and intensive functional exercises in bolstering subsequent functional recovery. Furthermore, rising living standards have prompted enhanced health expectations, thereby catalyzing a shift toward more precise and individualized treatment modalities.

In light of technological advancements, digital design and 3D printing technologies have garnered attention in recent years, attributed to their capability in facilitating preoperative planning and intraoperative navigation [2, 3], along with enhancing the efficacy of doctor-patient interactions [4, 5]. The application of digital technology for preoperative precision in skin flap design obviates the time-intensive processes inherent in traditional methods. This personalized approach heightens patient satisfaction. Concurrently, the fabrication of 3D models for surgical simulation offers an intuitive medium for comprehensive preoperative dialogue with patients, necessitating minimal consultations

https://doi.org/10.62347/MTJZ9462

while precluding the inefficiencies of redundant and fragmented discussions.

Yue Caixiang et al. [6] utilized computerized tomography angiography (CTA) in conjunction with Mimics software for digital design in 15 patients with hand soft tissue defects, facilitating the precise, personalized preoperative design of lateral arm perforator flaps. This approach not only guided surgical procedures but also conserved operating time, minimized risks, and contributed to satisfactory postoperative sensory and functional recovery of the flaps. Similarly, Qin Hao et al. [7] engaged in a study involving 16 patients with soft tissue defects on the dorsal hand. They executed preoperative assessments, securing donor foot and bilateral hand computerized tomography (CT) scans, which were subsequently integrated into Mimics software for 3D reconstruction and flap design. This digital technology assisted in the successful transplantation of flaps from the dorsum of the foot, addressing dorsal hand defects, thereby facilitating commendable postoperative hand aesthetics and functionality. In another study, Liu Qinghua et al. [8] encompassed 12 patients featuring 17 fingers with soft tissue defects, procuring preoperative 3D-CTA data to reconstruct 3D models by computer software, comprehending the vasculature dynamics within the donor site. This enabled the accurate, individualized design of flaps, mitigating surgical risk and culminating in higher patient satisfaction post-surgery. Nonetheless, reports on the implementation of digital design and 3D printing technology for fingertip defect flap transplantation remain scarce.

In the present study, 90 patients presenting with finger defects were enlisted, wherein surgical interventions, augmented by digital design and 3D printing technology, were employed. The subsequent sections detail the notable postoperative outcomes achieved.

Patients and methods

Patients

This study is a retrospective study. According to inclusion and exclusion criteria, between October 2019 and June 2021, 90 patients with fingertip defects were recruited at Puren Hospital. 90 patients signed informed consent, and the experimental plan was approved by the hospital ethics committee (Ethics review number: 202006190502). The study cohort was divided into two groups: 45 patients underwent surgical procedures facilitated by digital design and 3D printing technology (3D printing group), while the remaining 45 were treated using conventional pedicled flap transplantation and skin grafting methods (traditional surgery group).

Inclusion criteria were as follows: 1) Individuals presenting with fingertip defects confirmed by physical examination; 2) Preoperative digital design of the fingertip defect flap was performed; 3) Fingertip defect patients were briefed using a 3D printed model of the affected tip; 4) Availability of comprehensive follow-up data; 5) Voluntary participation in the study with informed consent obtained from patients and their families.

Exclusion criteria encompassed: 1) Patients presenting with historical digit defects; 2) Unwillingness to participate in the study; 3) Inability to secure complete follow-up data.

Methods

Traditional operation group method: Patients in the conventional surgery group underwent hospital admission for enhancement of pertinent preoperative assessments, with surgical plans devised preoperatively based on the surgeons' expertise. All participants exhibited negative preoperative examination results, devoid of prominent surgical contraindications. Following adequate anesthesia, exhaustive debridement was executed intraoperatively. The donor flap originated from either the ulnar or radial aspect of the compromised digit, incorporating the distal segment of the digital artery as the pedicle. The flap distal portion preserved approximately 1 cm of soft tissues, encompassing the homolateral digital neurovascular bundle. Flap dimensions ranged from 1.8 cm × 4.2 cm to 2.4 cm × 5.5 cm. Surgical teams incised the donor site skin adjacent to the affected finger in a tiered fashion, following the pre-established outline. Dissection of the proximal flap commenced proximally, proceeding distally along the neurovascular bundle superficial plane, with approximately 2 cm of the distal neurovascular structure being freed, and the utmost 1 cm incorporated within the soft tissue, concomitantly dissected with the flap. After comprehensive flap mobilization, a 180° rotation was conducted to overlay the finger's defect, followed by sequential suture of the flap. Full-thickness skin grafts facilitated the reconstruction of the donor site, concluded with pressurized bandaging.

3D printing group surgical method: A 3D scanner facilitated the scanning of the affected hand, and subsequent design modifications of the flap were executed using 3D reconstruction software. Following the import of files into the reconstruction software, a mirrored 3D model of the healthy hand was generated, yielding a 3D virtual model of the affected side. This virtual representation was then juxtaposed with the actual model of the affected hand. The surplus segment, indicative of the fingertip defect requiring repair, was demarcated, and the defect's area was quantified. An optimal donor site, coinciding in area, was identified adjacent to the affected finger. The intended donor flap, measuring between 1.9 cm × 4.3 cm and 2.5 cm × 5.6 cm, was delineated. Utilization of a shell extraction instrument simulated the intraoperative skin flap incision within the donor zone. The rotation axis was established at 1 cm proximal to the distal interphalangeal joint, dictating the pedicle's length from this rotational fulcrum to the wound's proximal extremity. Files in STL format were integrated into Cura 15.02.1, with parameter settings adjusted per literary documentation [10]. Subsequently, Gcode formatted files were imported into the 3D printing software, initiating the fabrication of 3D models.

The biological skin flap was aligned with the surface of the 3D model, and upon incision, the area congruent with the donor defect was delineated, representing the simulated transplant skin flap. The base of this simulated flap was anchored to the model, with the donor area's flap mobilization during surgery emulated through rotation. This method facilitated a 3D-printed model-assisted surgical process simulation, enabling preoperative discussions with the patient and their family. The operative technique employed paralleled that of the conventional surgery group.

Postoperative management and follow-up: Postoperative protocols mandated abstention from smoking and the maintenance of warmth in the affected limbs, accompanied by anticoagulation, anti-infection, and anti-spasticity measures as part of symptomatic treatment. Vigilant wound dressing changes were implemented, with skin graft pressure dressings slated for removal 7-10 days' post-surgery. Suture removal occurred on day 14 post-operation, followed by the cessation of external plaster fixation at the 3-week mark.

Patients underwent a follow-up period ranging from 6 to 24 months, with a mean duration of 15 months. Observations during this period included the aesthetic outcome of the affected finger, cold intolerance, and sensory recuperation of the skin flap. Concurrently, patients received guidance to intensify functional exercises targeting the finger and wrist joints. The recuperation of the finger flap was evaluated comprehensively, adhering to the hand function assessment criteria stipulated by the Hand Surgery Society of the Chinese Medical Association [11].

Main observation index

Comparative analysis was conducted on several parameters between the two groups. Main indicators include operation duration, flap anastomosis rate (determined by comparing the preoperative flap defect area with the actual incised flap area), and flap survival rate. Secondary indicators include aesthetic outcome of the affected finger, cold intolerance, sensory recuperation of the flap, and overall evaluation results. Operation duration was quantified post-procedure. Flap anastomosis and survival rates were assessed on the day preceding discharge, with the hospitalization period spanning 10-14 days. Aesthetic outcome, cold intolerance, sensory recuperation, and comprehensive assessment of the flap were documented during the 6-month follow-up.

Aesthetics (100 points): finger shape full 100 points; Slight atrophy of finger flap 80 points; Moderate atrophy 40 points; Severe atrophy of 20 points.

Cold resistance (100 points): skin color, temperature is normal, do not need special protection 100 points; The color is slightly poor, the temperature is slightly lower, afraid of cold 80 points; Pale skin or cyanosis, the temperature is obviously cool, especially afraid of cold 40

Table 1. Comparison of surgery-related indexes between the two groups (x±s, n=45)

Group	Time of operation (min)	Flap anastomosis rate (%)
3D group	50.40±5.25	94.00±2.30
Traditional operation group	64.67±4.39	86.53±3.68
t	-8.079	6.663
P	0.000	0.000

minutes; Dark or blue skin, cold days dare not expose 20 minutes.

The degree of skin sensation recovery (100 points): S4 sensation returned to normal, two-point resolution < 6 mm, 100 points; S3+: In addition to S3, there are some two-point discrimination, 80 points; S3: Full recovery of shallow pain and touch, no allergies, 60 points; S2 slight recovery of shallow sense and touch, 40 points; S1 skin deep pain recovery, 20 points; No sensation in the S0 neurojurisdiction, 0.

Statistical analysis

Statistical analysis was performed using SPSS 21.0 software, setting α at 0.05 for the significance level in intergroup comparisons. Measured data were presented as mean ± standard deviation, with the intergroup difference assessed using the independent samples t-test. Categorical data were expressed as case numbers and percentages (%), with the Chi-square test or Fisher's exact test employed for intergroup comparisons. The Mann-Whitney U test was used for non-parametric analyses between data sets.

Results

Comparison of general information between the two groups

Demographically, the 3D printing group consisted of 35 males and 10 females, ages ranging from 18 to 55 years with a mean age of 31. Injury types included 13 crush injuries, 21 lacerations, and 11 avulsions. According to the Allen classification [9], the distribution was as follows: 15 type II injuries, 17 type III, and 13 type IV. In contrast, the traditional surgery group comprised 30 males and 15 females, spanning ages 20 to 58 years with an average age of 32. Injury categorization revealed 17 crush injuries, 17 lacerations, and 11 avulsions, with 19 type II, 11 type III, and 15 type IV cases based on the Allen classification. Statistical analysis demonstrated no significant discrepancies in gender distribution, age, injury causation, or other baseline characteristics between the groups, affirming their comparability (P > 0.05).

Comparison of surgery-related indexes between the two groups

t-test analysis of two independent samples revealed a significant difference in operation time and flap anastomosis rate between the two groups (P < 0.05). The 3D printing group demonstrated a considerably shorter operation time and a markedly higher flap anastomosis rate compared to the traditional surgery group, detailed in **Table 1**.

Comparison of skin flap recovery between two groups

Statistical analysis indicated no significant disparities in the survival rate, aesthetic outcome, or cold resistance of the skin flaps between the two cohorts (P > 0.05), detailed in **Table 2**.

Comparison of postoperative follow-up results between the two groups

Using the Mann-Whitney U test, the investigation discerned no significant variances in sensory recovery or the comprehensive appraisal of skin flap health between the groups under comparison (P > 0.05), as elucidated in **Table 3**.

Typical case analysis

Case Report: A male patient, 42, presented with a soft tissue defect at the distal phalanx of his left ring finger following a mechanical strangulation incident, leaving tendons and bone exposed. Initial management involved debridement, followed by wound reconstruction employing 3D surgical techniques. Digital planning and 3D printing facilitated precise preoperative strategizing and consultation for the requisite flap transplantation in addressing the fingertip

Table 2. Comparison of skin flap recovery between the two groups (n/%, n=45)

Group	Survival rate	Aesthetic degree	Cold endurance
3D group	45/100.0	44/97.8	44/97.8
Traditional operation group	43/95.6	41/91.1	40/88.9
χ^2/*Fisher*	-#	1.875*	0.000*
P	1.000	0.171	1.000

Note: *: Chi-square test; #: Fisher's exact test.

Table 3. Comparison of postoperative follow-up results between the two groups (n=45)

Group	Degree of sensory recovery in the flap					Comprehensive assessment		
	S1	S2	S3	S3+	S4	A	B	C
3D group	0	2	7	14	22	36	9	0
Traditional operation group	0	8	9	11	17	28	17	0
Z			-1.689				-0.888	
P			0.090				0.374	

Note: S1, S2, S3, S3+, S4 respectively; S1 indicates the recovery of deep skin pain; S2 indicates a slight recovery of shallow sense and touch; S3 indicates that the shallow pain and touch are completely restored, and there is no allergy; S3+ indicates that apart from S3, there is still some two-point discernment; S4 indicates that the feeling is back to normal, and the two-point resolution is < 6 mm.

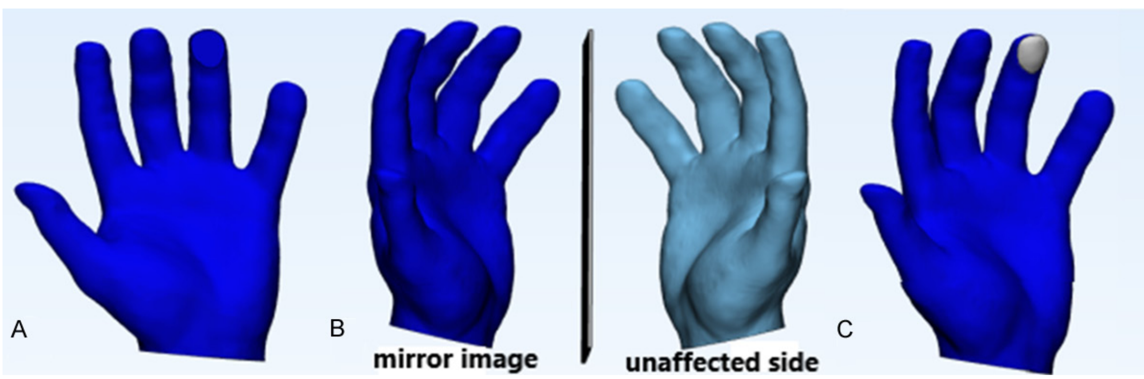

Figure 1. Digital design combined with 3D printing applied to fingertip defect flap transplantation. Note: (A) shows the hand model of the affected side generated by 3D reconstruction software; (B) generates the image virtual model of the healthy side for the image; (C) is to obtain the part to be repaired (white part) by comparing the virtual model of the healthy side and the hand model of the affected side (blue model).

defect (**Figure 1**). In alignment with the preoperative blueprint, the flap meticulously excised from the lateral aspect of the finger adequately supplanted the deficit at the digit's extremity, exhibiting satisfactory vascular perfusion. Harvested full-thickness skin grafts from an appropriate donor site were used for complementary repair, succeeded by pressure dressings. A 9-month postoperative evaluation revealed a pliable flap consistency, aesthetically pleasing recovery, with skin pigmentation closely mirroring normal hues. Sensory functions were reestablished, devoid of complications such as interphalangeal joint mobility impairment or donor-site discomfort. The holistic appraisal of the postoperative flap yielded a score of 96 (refer to **Figure 2**).

Discussion

Fingertip defects remain among the prevalent forms of hand injury, necessitating an array of surgical interventions, each encompassing distinct merits and limitations. Strategies addressing these defects range from occlusive medicament application to local, homodigital, heterodigital, and free flap transplantation [12-17]. Local advanced flap transplantation, estab-

Figure 2. Preoperative and postoperative results of fingertip defect flap transplantation. Note: In (A and B), the left ring finger is completely severed at the end (Allen type III); (C) is the donor flap; (D and E) were to cover the finger tip defect, and the donor area was grafted with pressure bandaging; (F-H) was 6 months post-operative follow-up, and the flap recovered well.

lished as a predominant reparative approach since the 1960s, has undergone consistent refinement, paving the way for the advent of innovative techniques and operational methodologies in fingertip defect management [18]. Contemporary practice commonly employs various reconstructive modalities, including digital artery retrograde island flap, adjacent digital island flap, proximal digital pedicle flap, dorsal digital fascial flap, and free digital lateral flap procedures [19, 20]. These traditional surgical avenues have attained a level of maturation, signifying their established role in clinical scenarios.

Currently, the preoperative planning of fingertip defect flap transplantation predominantly relies on the surgeon's subjective assessment. This conventional method involves covering the affected finger with a thin paper or rubber glove, approximating the donor site's flap size based on the surgeon's prior experience, and delineating an area congruent with the defect post-excision, referred to as the template. This template is then positioned adjacent to the compromised digit, guiding the marking of the donor site perimeter. Subsequent steps include detailed procedural planning and execution. Traditional skin flap preoperative planning suffers from inherent subjectivity, prompting the introduction of a digital surgical blueprint for fingertip defect flap transplantation. This innovative approach entails virtual software-based design tailored to the patient's specific injury parameters, culminating in the 3D printing of the affected fingertip model. A biological flap is mapped onto the 3D model's surface, and post-excision, the area aligning with the donor defect is identified, simulating the transplanted flap. This methodology decisively addresses the imprecision, lack of scientific rigor, and standardization resulting from reliance on subjective expertise and arbitrary donor site estimation. It efficiently precludes discrepancies between the actual flap dimensions and the intended coverage area on the amputated finger. Concurrently, by securing the simulated flap's base on the model and maneuvering the flap within the donor zone during surgery, the process enhances the tangibility of preoperative discussions, significantly bolstering doctor-patient communication.

The principal benefits of integrating digital design with 3D printing technology encompass: (1) Enhancing preoperative precision in flap configuration, thus obviating the temporally extensive conventional methodology; (2) Facilitating a patient-centric approach to flap design, thereby raising patient satisfaction levels; (3) Prior flap planning contributes to the conservation of operative duration, minimizes the timeframe for tourniquet application on the involved extremity, expedites the reestablishment of blood circulation to the compromised digit, and augments flap viability.

Conversely, the primary limitations of fusing digital design with 3D printing technology [21] include: (1) escalation in clinical workload; (2) the necessity for interdisciplinary collaboration arising from the multifaceted nature of 3D printing processes; (3) increased patient's medical cost: the total hospital cost of traditional surgery is 25,000-30,000 RMB, of which the surgical cost is about 10,000 RMB. Use of 3D printing technology will increase the cost by 2000-3000 RMB.

Digital and 3D printing technologies herald an innovative paradigm for the management of finger defects through flap transplantation, but need empirical validation through extensive case studies in clinical settings. Advancements in digital modalities, enhancements in the precision and material quality of 3D printing, and refinements in surgical instruments and methodologies, along with intensified interdisciplinary cooperation, are projected to expand the therapeutic prospects for hand trauma.

Acknowledgements

This work was supported by the Qingdao Science and Technology Benefit the People Demonstration Project (No. 23-2-8-smjk-7-nsh) and 2023 Joint Fund Project of Hubei Key Laboratory of Occupational Hazard Identification and Control (JF2023-K01).

Disclosure of conflict of interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Address correspondence to: Rong Liu, Institute of Medical Innovation and Transformation, Puren Hospital Affiliated to Wuhan University of Science and Technology, Wuhan, Hubei, China. E-mail: dr_liurong@whu.edu.cn; Xuexiao Ma, Department of Spinal Surgery, The Affiliated Hospital of Qingdao University, Qingdao, Shandong, China. E-mail: maxuexiaospinal@163.com

References

[1] Lok LW, Chan WL and Lau YK. Functional outcomes of antegrade homodigital neurovascular island flaps for fingertip amputation. J Hand Surg Asian Pac Vol 2017; 22: 39-45.
[2] Wang X, Xu S, Zhou S, Xu W, Leary M, Choong P, Qian M, Brandt M and Xie YM. Topological design and additive manufacturing of porous metals for bone scaffolds and orthopaedic implants: a review. Biomaterials 2016; 83: 127-141.
[3] Wieding J, Wolf A and Bader R. Numerical optimization of open-porous bone scaffold structures to match the elastic properties of human cortical bone. J Mech Behav Biomed Mater 2014; 37: 56-68.
[4] Partridge R, Conlisk N and Davies JA. In-lab three-dimensional printing: an inexpensive tool for experimentation and visualization for the field of organogenesis. Organogenesis 2012; 8: 22-27.
[5] Mulford JS, Babazadeh S and Mackay N. Three-dimensional printing in orthopaedic surgery: review of current and future applications. ANZ J Surg 2016; 86: 648-653.
[6] Yue C, Cao Y, Feng L and Zhao L. Application of digital technology in the lateral arm perforator flap for reconstruction of soft tissue defect of hand. Chin J Microsurg 2019; 42: 344-347.
[7] Qin H, Tan H, Wei P, Li X, Huang G, Luo X, Xu L, Mo Y and Liang X. Digital technique assisted dorsal foot flap transplantation to repair soft tissue defect of dorsal hand. Chin J Microsurg 2019; 42: 53-56.
[8] Liu Q, Zhang M and Liu C. Repair of thumb and finger soft tissue defects by digital technology assisted toe tissue transplantation: a report of 12 cases. Chin J Microsurg 2018; 41: 548-551.
[9] Allen MJ. Conservative management of finger tip injuries in adults. Hand 1980; 12: 257-265.
[10] Zhu B. Research on Pro/E-Cura 3D printing process technology. Science and Technology Outlook 2014; 149.
[11] Pan S, Gu Y and Shi D. The trial standard of upper extremity function evaluation of hand surgery society of Chinese medical association. Chin J Hand Surg 2000; 16; 130-135.
[12] Lee Y, Woo SH, Kim YW, Lee YH and Baek GH. Free flaps for soft tissue reconstruction of digits. Hand Clin 2020; 36: 85-96.

[13] Tang JB. Fingertip repair methods: choices for different fingers and sides emphasizing sensation. J Hand Surg Eur Vol 2019; 44: 1109-1111.
[14] Tos P and Adani R. Finger amputations and pulp defects distal to the distal interphalangeal joint. J Hand Surg Eur Vol 2019; 44: 1105-1106.
[15] Wang H, Yang X, Chen C, Huo Y, Wang B and Wang W. Modified heterodigital neurovascular island flap for sensory reconstruction of pulp or volar soft tissue defect of digits. J Hand Surg Am 2020; 45: 67.e1-67.e8.
[16] Adani R, Marcoccio I, Tarallo L and Fregni U. The reverse heterodigital neurovascular island flap for digital pulp reconstruction. Tech Hand Up Extrem Surg 2005; 9: 91-95.
[17] Tang JB, Elliot D, Adani R, Saint-Cyr M and Stang F. Repair and reconstruction of thumb and finger tip injuries: a global view. Clin Plast Surg 2014; 41: 325-359.
[18] Chen J. Research progress in the treatment of finger wound. Chin J Trauma 2018; 34: 663-669.
[19] Li Q, Bian C, Zhu W and Li Q. Island flap of dorsal branch of proper digital artery of long pedicled adjacent finger to repair lateral tissue defect of middle and distal finger. Chin J Hand Surg 2015; 31: 340-342.
[20] Gao Z, Zhang J and Lei Y. Fingertip defect was repaired with free nerve flap of foot toe peroneal artery. Chin J Hand Surg 2015; 31: 398.
[21] Lu H, Peng H, Peng Z, Liu D, Wu Q and Liu R. The application of digital design combined with 3D printing technology in skin flap transplantation for fingertip defects during the COVID-19 epidemic. Biomed Res Int 2021; 2021: 5554500.