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CLINICAL APPLICATION OF 3D PRINTING TECHNOLOGY FOR PREOPERATIVE PLANNING OF THUMB RECONSTRUCTION

APLICAÇÃO CLÍNICA DA TECNOLOGIA DE IMPRESSÃO 3D PARA PLANEJAMENTO PRÉ-OPERATÓRIO DE RECONSTRUÇÃO DE POLEGAR

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ABSTRACT

Objective: This study aimed to explore the clinical application of preoperative precise design for 3D printing and thumb reconstruction, which could help manage the patients with thumb defect and achieve better function and appearance. Methods: This was a retrospective study of 20 patients who underwent the surgery of harvesting toe transplant and thumb reconstruction between January 2015 and December 2016. The 3D model of the thumb defect was created and printed. The dimensions of skin and bones from donor site were precisely designed as reference for surgical operation. The surgery was performed according to the model. Results: Perfect repair of defects was achieved with satisfying appearance and function. The reconstructed thumbs all survived (survival rate of 100%). Follow-up was 3-9 months. The maximum dorsiflexion was 8-30° and the maximum flexion was 38-58°. The two-point sensory discrimination was 9-11 mm. In total, 17 patients reposted "Excellent" satisfaction and three "Good", each for the reconstructed thumb and hand function, respectively. The satisfaction rate was 85%. Conclusion: Preoperative digital design and 3D printing according to the donor and recipient sites allowed a tailored operation. The operation was more precise, the appearance of the reconstructed thumb was good. ***Level of Evidence II, Retrospective Study***.

Keywords: Finger Injuries. Bone Transplantation. Reconstructive Surgical Procedures. Printing, Three-Dimensional. Computer-Aided Design.

RESUMO

Objetivo: Este estudo explorou a aplicação clínica do desenho pré-operatório preciso para impressão 3D e reconstrução do polegar, para ajudar no controle e melhorar função e aparência. Métodos: Estudo retrospectivo de 20 pacientes submetidos à cirurgia de colheita de transplante de dedo do pé e reconstrução do polegar entre janeiro de 2015 e dezembro de 2016. O modelo 3D do defeito do polegar foi confeccionado e impresso. As dimensões da pele e dos ossos da área doadora foram precisamente projetadas como referência para a operação cirúrgica, realizada de acordo com o modelo. Resultados: O reparo perfeito foi alcançado com aparência e função satisfatórias. Todos os polegares reconstruídos sobreviveram (taxa de sobrevivência de 100%). O acompanhamento foi de 3-9 meses. A dorsiflexão máxima foi de 8-30° e a flexão máxima foi de 38-58°. A discriminação sensorial de dois pontos foi de 9-11 mm. No total, 17 pacientes reportaram índice "Excelente" e três índice "Bom" cada para a função reconstruída do polegar e da mão, respectivamente. O índice de satisfação foi de 85%. Conclusão: O design digital pré-operatório e a impressão 3D de acordo com os locais doador e receptor permitiram uma operação customizada. A operação foi mais precisa, com bom aspecto. ***Nível de Evidência II, Estudo Retrospectivo.***

Descritores: *Traumatismos dos Dedos. Transplante Ósseo. Procedimentos Cirúrgicos Reconstrutivos. Impressão Tridimensional. Desenho Assistido por Computador.*

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INTRODUCTION

Thumb trauma can lead to dramatic effects on the functions of the hand, witch shows an urgent need for a more rational and standardized surgical approach to achieve thumb reconstruction with the best function and appearance, high safety and effectiveness profiles, and with minimal donor site injury.[1] The applications of 3D printing in medicine include preoperative planning, simulation of fracture reduction, prosthesis customization, tissue engineering, doctor patient communication, and

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The study was conducted at Guangxi Clinical Research Center for Digital Medicine and 3D Printing, Guigang City People's Hospital.
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medical education.[2] As for thumb reconstruction surgery, surgical models and customized prosthesis can be made by 3D printing according to the specific condition of the patient, which not only simplify the surgical operation and reduce the operation time, but also enhance the surgical quality and therapeutic effect with reduced surgical risk.[2-6]

This study aimed to explore the clinical application of preoperative precise design for 3D printing and thumb reconstruction. The results could help manage the patients with thumb defect and achieve better function and appearance.

MATERIALS AND METHODS

Study design and patients

This was a retrospective study of 20 patients who underwent the surgery of harvesting toe transplant and for thumb reconstruction between January 2015 and December 2016. The study was approved by ethics committee of our hospital and has been performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. An informed consent form was signed by each patient.

The inclusion criteria were: 1) the metacarpophalangeal joint (MP) of the injured thumb was good; 2) the thumb injury occurred within 2 years; 3) third degree thumb defect, including IIIa (proximal phalanx defect) and IIIb (loss of proximal phalanx and across the base). The exclusion criteria were: 1) chronic osteomyelitis, bone and joint tuberculosis, synovitis, and diabetes mellitus; 2) defect of the first metacarpophalangeal joint of the injured thumb; or 3) both thumb were injured.[7]

Preoperative planning and digital design

Figure 1 presents the imaging workflow. Preoperative 64-row dual source spiral computed tomography (CT) scanning (SIEMENS, Erlangen, Germany) was performed for donor foot and injured hands. Feet CT angiography (CTA) was also performed to reconstruct the foot skeleton and blood vessels, so that the relationship between the bone and the first dorsal metatarsal artery was determined before operation.[8] Iohexol (370 mg I/ml) was injected through the median cubital vein and the hands were scanned using 64-row dual source spiral CT at 120 kV and 110 mA, thickness of 1 mm, matrix of 512×512, and scanning time of 200 ms. The CT images of donor foot and hands were imported into the Mimics 14.0 software as DICOM format, and converted into 3D images of bone and soft tissues. Given the symmetrical characteristics of hands and feet, the mirror image of the healthy thumb was created by using the Cutwith Curve software, and overlapped with the injured thumb using the Move and Rotate tools. The accurate size, area, and shape of the thumb defect could be accurately calculated, and segmented using the Cut with Curve tools. The segmented part was the real defect region. The study was approved by ethics committee of our hospital and has been performed in accordance with The ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. An informed consent form was signed by each patient.

3D printing and simulation operation

The thumb reconstruction strategy was determined according to the thumb defect type. The model of the defect region created from the mirror image was moved to the donor foot site by using the Move and Rotate tools. The projection of the model on the donor sites was used as the operation markers, but 0.2 and 0.3 mm larger. The incision to expose the flap's blood vessel was made according to the preoperative CT post-processed CTA image with volume rendering. Similarly, the length of the vascular pedicle was calculated according to the thumb defect.

The model of reconstructed skin and tissue was printed using a 3D printer, and the length as well as the size of skin and bone from the donor site could be accurately calculated, which could be used for donor tissue dissection and designed individually before operation. The whole process was more standardized and accurate, with more real-like appearance and minimized donor injury.

The individualized 3D model was created by simulation reconstruction through the Mimics medical software. The model was then imported into the makew-are software to adjust its position and inclination angle, and exported as x3g format for SD disk saving. Then, the models of bone and skin soft tissues were printed using a MakerBot 3D printer (MakerBot, New York City, NY, USA). Adhesive plaster was used to apply to the surface of the model, and used as template for donor site operation after cutting into pieces.

The adhesive plaster applied to the surface of the 3D model was peeled apart. The peeled adhesive plaster was applied to the donor site, and the line was made according to the adhesive plaster, which was used as marker to indicate the size and shape of the flap.

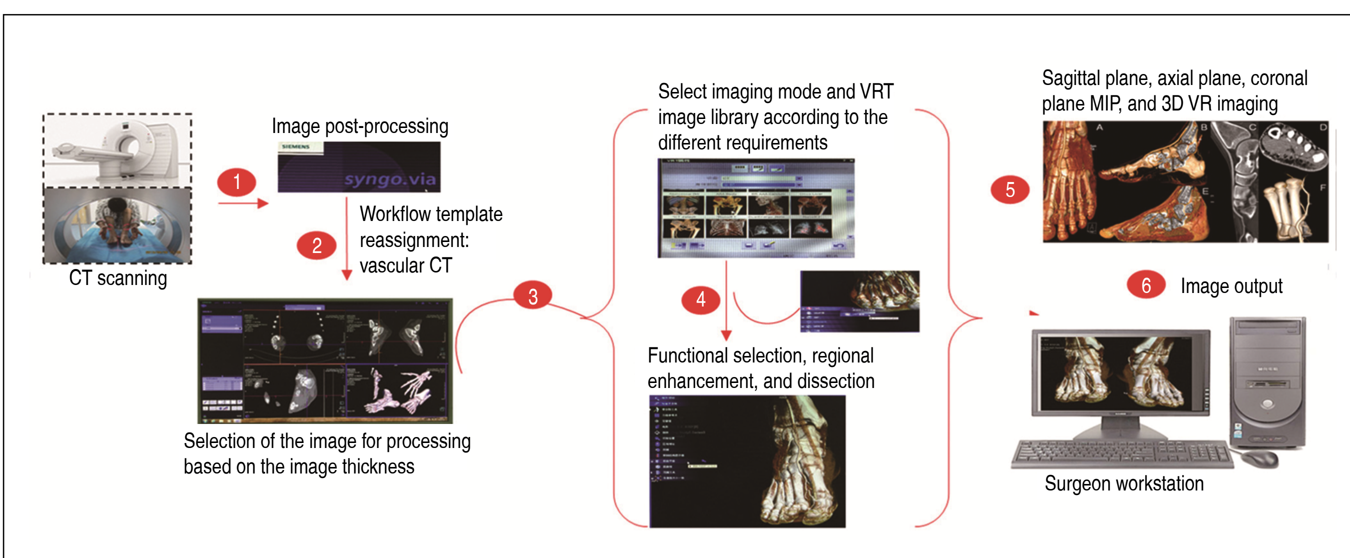

Figure 1. Imaging workflow.

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Surgical considerations

The surgical mode was selected based on the thumb defect: 1) toe paratelum or toenail flap reconstruction for I° and II° defects, and toenail flap or second toe reconstruction for III° defect; 2) toe fibular ventral skin flap reconstruction for thumb pulp defect; 3) toe distal with nail flap reconstruction for degloving injuries of the thumb skin; 4) reconstruction of the second toe of the dorsum pedis flap with fibular helm and metatarsophalangeal joint, or reconstruction of the second toe and tendon tissue flap combined with metatarsophalangeal joint reconstruction for IV° defect; and 5) reconstructing of contralateral second toe with the rhomboid dorsalis pedis flap and metatarsophalangeal joint for V° and VI° defects. The size and length of the thumb defect were confirmed by preoperative digital imaging and 3D printing and projected to the donor size. The precise incision not only facilitated reconstruction and appearance improvement, but also helped the functional recovery. The donor toe paratelum phalanx with suitable length was fixed with the basal area of the phalangette for the distal phalanx of finger defect with intact distal interphalangeal joint. If the distal interphalangeal joint was injured, the suitable length of the paratelum phalanx of second toe was kept fixing with the middle phalanx of finger. The distal interphalangeal joint of hand was reconstructed with the distal interphalangeal joint of toe. The bone fixation was mainly dependent on wire cross strapping or Kirschner wire.

The design circumference of the flap pedicle from the harvested toe had to be 15-20% larger than that of the actual defect, in order to avoid skin suture tension, prevent flap atrophy, and maintain blood supply. The length of the dissociated vascular pedicle had to be appropriate; too short pedicle could lead to increased tension of vascular anastomosis; too long pedicle could result in the zigzagging blood vessels and poor blood supply.[9]

Surgery

The incision mark was made on the great toe based on the preoperative design strategy according to the skin, nerve, blood vessel, and tendon defects on the thumb. The edematous nerves and inflammatory necrotic vascular bundles were also removed.[10]

The skin and subcutaneous tissue were opened according to the pre-designed marker. The first dorsal metatarsal artery, dorsalis pedis artery, great saphenous vein of dorsal foot, dorsal venous arch of foot, and dorsal vein of second toe were dissected. The osteotomy was conducted according to the length of the 3D printed model. After the great toe flap was dissected, the bone was fixed with Kirschner wire of 1.0 mm diameter. The extensor digitorum longus tendon and the flexor digitorum longus tendon were sutured.[11] Anastomosis of nerves and vessels was conducted under the microscope. If the tension was excessive, a full-dimension skin flap on the same side thigh was obtained to cover the incision and fixation.[12]

Postoperative management

Conventional treatment and nursing after amputated finger replantation and thumb reconstruction were performed including warm preservation, anti-convulsion, anti-coagulation, and anti-infection.

A monthly review at our hospital was suggested for all patients, and the follow-up period lasted 3-9 months (6 months in average). The length, thickness, appearance, flexion and extension, strength of grasping and griping, and sensory evaluation such as two-point sensory discrimination and Michigan Hand Outcomes Questionnaire (MHQ)[13] scores were performed.

Statistical analysis

Continuous data were tested for normal distribution using the Kolmogorov-Smirnov test. Normally distributed continuous data were presented as mean ± standard deviation and analyzed using the paired t test. Non-normally distributed data were presented as median (range) and analyzed using the Wilcoxon test. Categorical data were presented as frequencies and analyze d using the Fisher exact test. All analyses were conducted using SPSS 16.0 (IBM, Armonk, NY, USA). Two-sided P-values <0.05 were considered statistically significant.

RESULTS

Characteristics of the patients

In total, 13 men and 7 women participated in this study. Their age ranged between 2 and 45 years old. The causes of injury included machinery accident for 12 patients, plate planer injury for three patients, and chainsaw injury for five patients (Table 1).

Table 1. Characteristics of the patients

Case	Age (years)	Degree of thumb defect	Defect of the first web	Length of required thumb (mm)	Width of healthy toe (mm)	Thickness of healthy digital pulp (mm)
1	22	I	Yes	32	16	15
2	23	II	Yes	31	15	14
3	29	IIIa	No	42	18	17
4	2	IIIa	No	22	12	12
5	34	IIIb	Yes	41	16	14
6	45	IIIa	No	37	17	15
7	28	IIIb	Yes	38	17	16
8	31	IIIa	Yes	31	13	12
9	44	II	No	32	14	14
10	27	IIIa	No	33	13	13
11	11	IIIa	Yes	31	14	13
12	38	IIIb	No	41	17	15
13	39	I	Yes	35	16	14
14	41	IIIa	No	44	17	15
15	29	IIIb	No	46	18	16
16	30	IIIa	Yes	46	17	15
17	33	II	No	32	14	14
18	29	IIIa	No	37	15	13
19	27	IIIa	Yes	38	16	13
20	21	IIIb	Yes	39	16	14

3D models

The models of defect tissues and bones were 3D-printed for 20 patients with thumb reconstruction. Perfect repair of defects was achieved with satisfying appearance and function (Table 2). The reconstructed thumbs all survived (survival rate of 100%).

Table 2. Post-surgical outcomes of 20 thumb reconstructions using a 3D-printed model.

Case	Age (years)	Time of operation (h)	Length of reconstructed thumb (mm)	Width of nail (mm)	Thickness of digital pulp (mm)	Satisfaction
1	22	6.1	33	16	10	Excellent
2	23	6.2	30	15	9	Excellent
3	29	6,0	41	17	10	Excellent
4	2	5.9	25	13	8	Good
5	34	6.4	40	18	10	Excellent
6	45	6.1	36	16	11	Excellent
7	28	6.7	37	16	9	Excellent
8	31	6.9	32	15	10	Good
9	44	7.2	33	15	9	Excellent
10	27	6.8	32	15	10	Excellent
11	11	6.1	31	15	9	Excellent
12	38	6.7	40	18	10	Excellent
13	39	6.9	36	16	8	Excellent
14	41	7.2	43	18	10	Excellent
15	29	6.8	44	19	11	Good
16	30	6.1	45	19	9	Excellent
17	33	6.7	31	14	10	Excellent
18	29	6.9	35	14	9	Excellent
19	27	7.2	36	16	9	Excellent
20	21	6.8	37	15	9	Excellent

Follow-up

The postoperative follow-up was conducted for 3-9 months (6 months in average). The length of reconstructed thumb ranged 25-45 mm, with a thickness of 8-11 mm. The maximum dorsiflexion was 8-30° and the maximum flexion was 38-58°. The two-point sensory discrimination was 9-11 mm. The Michigan Hand Outcomes Questionnaire (MHQ) was performed, and the general score was 25.0-69.1%, the work score was 25-45%, the pain score was 38-73%, the appearance score was 17.1-31.1%, the final score was 12.5-47.0%, and the Michigan Hand Outcome score was 26-45%. The strength assessment showed that the key inch was 31-56% and the grip power was 31-54%. The results of functional evaluation for all reconstructed thumbs were satisfactory, with 'Excellent' 17 cases and 'Good' 3 cases. The satisfaction rate was 85% (Tables 2, 3, and 4).

Table 3. Post-surgical functions of 20 thumb reconstructions using a 3D-printed model.

Case	Age (years)	Gilbert's classification of FDMA	Function of thumb opposing (cm)	Mobility of MP (angle of extension and flexion)	Two-point discrimination (mm)	Condition of using hand
1	22	Ia	0.9 (<1.0)	Extension 30˚, flexion 50˚	9	Excellent
2	23	IIb	1.5 (1.0-2.0)	Extension 21˚, flexion 55˚	10	Excellent
3	29	IIa	0.9 (<1.0)	Extension 20˚, flexion 38˚	11	Excellent
4	2	IIa	0.8 (<1.0)	Extension 11˚, flexion 40˚	9	Good
5	34	IIb	1.1 (1.0-2.0)	Extension 14˚, flexion 45˚	10	Excellent
6	45	IIa	1.5 (1.0-2.0)	Extension 10˚, flexion 58˚	11	Excellent
7	28	IIb	0.9 (<1.0)	Extension 8˚, flexion 40˚	9	Excellent
8	31	Ib	1.4 (1.0-2.0)	Extension 12˚, flexion 45˚	10	Good
9	44	Ia	0.5 (<1.0)	Extension 15˚, flexion 55˚	11	Excellent
10	27	IIa	0.0(<1.0)	Extension 28˚, flexion 40˚	9	Excellent
11	11	IIb	0.7 (<1.0)	Extension 30˚, flexion 45˚	10	Excellent
12	38	Ia	0.9 (<1.0)	Extension 10˚, flexion 50˚	11	Excellent
13	39	Ib	1.3 (1.0-2.0)	Extension 5˚, flexion 58˚	9	Excellent
14	41	IIb	1.5 (1.0-2.0)	Extension 10˚, flexion 40˚	10	Excellent
15	29	IIb	1.4 (1.0-2.0)	Extension 11˚, flexion 45˚	9	Good
16	30	IIa	1.3 (1.0-2.0)	Extension 7˚, flexion 55˚	9	Excellent
17	33	IIb	1.2 (1.0-2.0)	Extension 13˚, flexion 57˚	10	Excellent
18	29	Ia	1.1 (1.0-2.0)	Extension 20˚, flexion 38˚	11	Excellent
19	27	IIa	0.7 (<1.0)	Extension 27˚, flexion 55˚	9	Excellent
20	21	Ib	0.5 (<1.0)	Extension 18˚, flexion 45˚	9	Excellent

Table 4. Michigan Hand Outcomes Questionnaire and strength assessment of 20 thumb reconstructions using a 3D-printed model.

Case	Gender	Fellow-up (months)	Michigan Hand Outcomes Questionnaire						Strength	
			General score (%)	Work score (%)	Pain score (%)	Appearance score (%)	Final score (%)	Michigan Hand Outcome Score (%)	Key pinch (%)	Grip power (%)
1	Male	6	25	25	50	18.8	16.7	26	45	39
2	Female	7	45	43	57	20.1	32.5	45	55	48
3	Male	9	66.2	44	64	20.1	32.9	43	43	35
4	Male	6	69.1	45	55	31.3	37.5	55	56	45
5	Male	7	40.1	34	52	22.4	20.4	32	55	43
6	Male	8	48.9	21	55	31.2	31.4	33	50	44
7	Male	6	52.4	29	58	29.1	30.1	37	51	48
8	Female	6	30.9	25	40	18.8	12,5	27	41	36
9	Male	8	33.2	37	41	27.1	18.4	29	41	32
10	Male	9	30.2	42	42	29.8	19.1	30	52	36
11	Male	6	37.7	44	38	27.4	21.8	32	43	42
12	Male	7	32.4	20	70	25.2	45.8	37	48	42
13	Female	6	36,4	38	73	27.3	44.3	39	50	46
14	Male	7	42.2	37	68	17.1	42.1	40	55	54
15	Male	9	42.9	26	64	19.1	47.2	44	48	32
16	Male	9	45.1	26	61	18.4	36.2	42	49	42
17	Male	6	45.0	37	57	25.2	28.1	40	41	49
18	Female	6	34.4	34	52	27.3	27.6	28	31	45
19	Male	6	45.2	42	61	17.1	32.7	29	39	31
20	Male	6	45.5	42	60	19.1	37.1	21	54	37

Typical cases

Case 1 was a 2-year-old boy, with distal phalanx complete amputation of right thumb. And Case 2 was an 11-year-old boy, with left thumb amputation. Both were injured by machine and performed replantation in emergency, that failed. Before toe transplantation, CTA was performed to obtain 3D information of the first dorsal metatarsal artery regarding to type, origin, route, and branches distribution. The whole picture of amputated thumb was created based on the other healthy hand through digital design, so that reconstruction model for amputated thumb was obtained. Then, reconstruction model was 3D-printed, and medical adhesive plaster was attached to 3D reconstruction model. Through that, first toe flap template was obtained by cutting medical adhesive plaster along 3D reconstruction model.

Both cases were used first toenail flap harvesting and transplantation for thumb reconstruction. The operations were conducted in accordance with preoperative designs (Figure 2, 4 and 5). Reconstructed thumbs of them survived with grade I wound healing and were follow-up regularly. Appearances of reconstructed thumbs were close to normal one 6 months after reconstruction. Grasp, holding, kneading, and thumb opposition were basically normal (Figure 3 and 6). The two-point sensory discrimination was 6 and 8 mm, respectively.

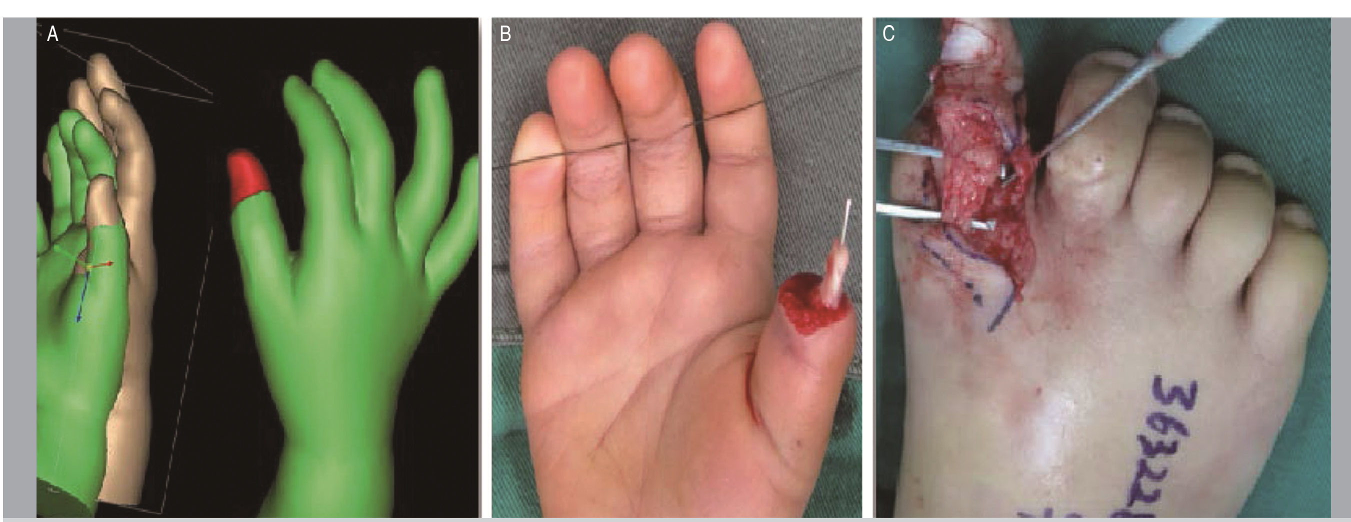

Figure 2. Reconstruction of the thumb tip by digital design and intraoperative operation. A: Digital design. B: Injured hand. C: Harvesting of the toe.

Figure 3. Six months after thumb reconstruction. A: Appearance comparison of the reconstructed thumb. B: Grasp function of the reconstructed thumb with interphalangeal joint flexion of about 90°. C: Donor area appearance.

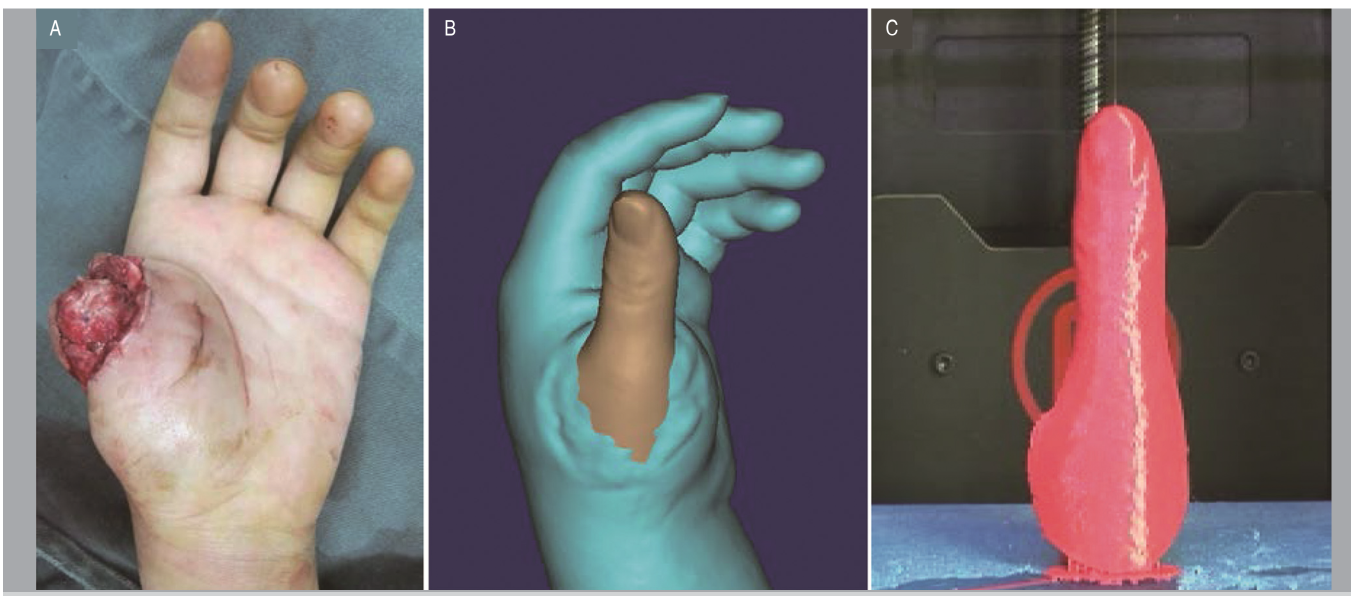

Figure 4. Preoperative design for thumb reconstruction. A: Left hand wound. B: Simulation of the reconstructed left thumb. C: Model printing.

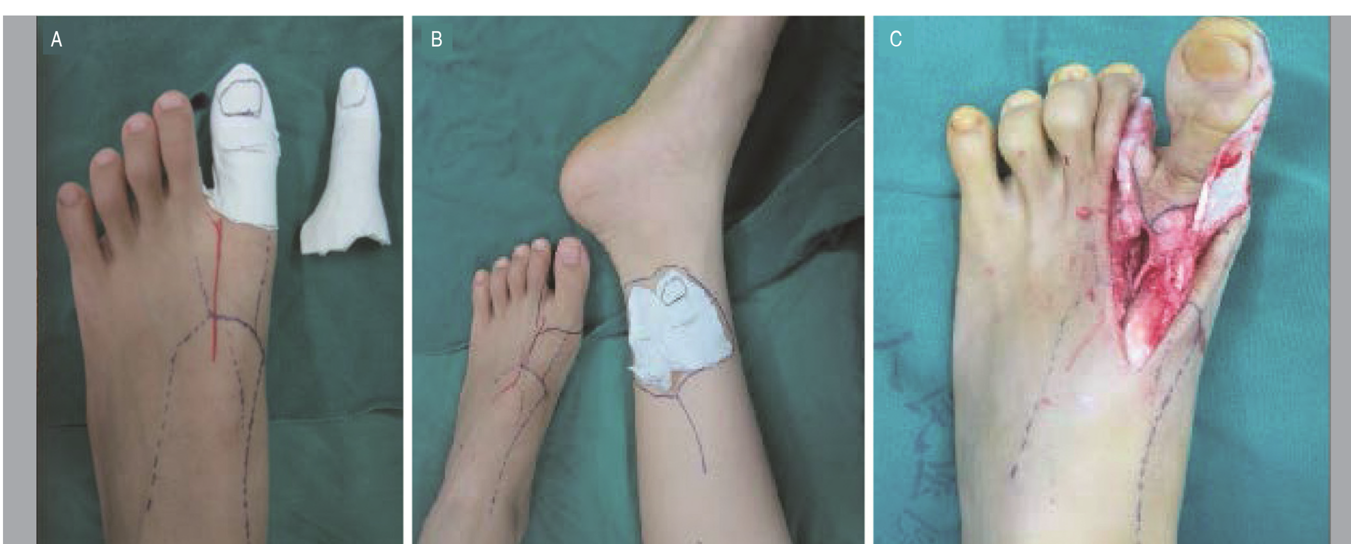

Figure 5. Operation for thumb reconstruction. A: Fabric design attached to the left food in order to mark the blood vessels and incisions. B: Fabric design attached to donor foot. C: Dissociated left great toe.

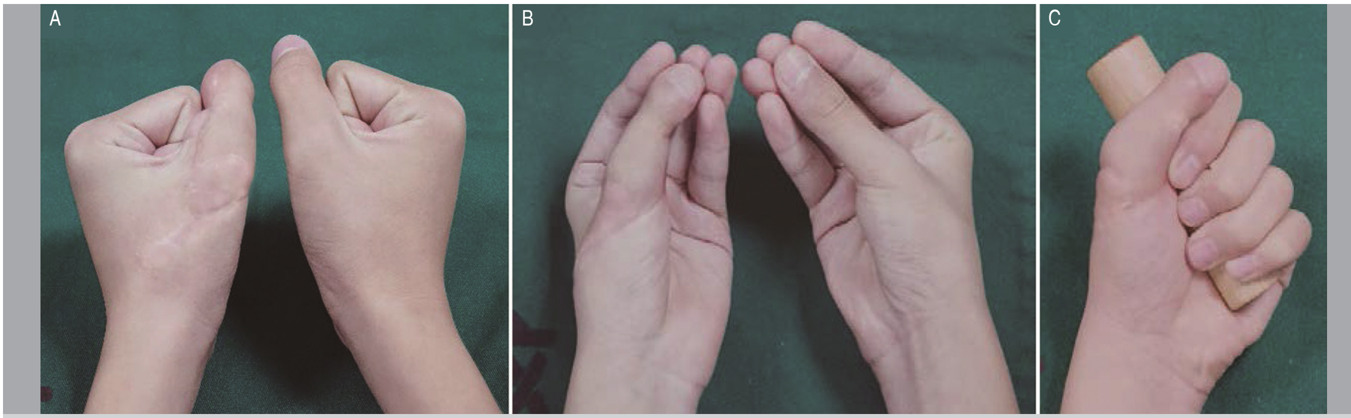

Figure 6. Six months after thumb reconstruction. A: Grip function of the two hands. B: Opposite function of the two hands. C: Holding function of the left hand.

DISCUSSION

3D printing has been suggested to potentially improve the outcomes of limb reconstruction.[2-6] This study aimed to explore the clinical application of preoperative precise design for 3D printing and thumb reconstruction. The results showed that preoperative digital design and 3D printing according to the donor and recipient sites allowed a tailored operation. The operation was more precise, the appearance of the reconstructed thumb was good, and the donor injury was minimal. The objectives of thumb reconstruction included the restoration of thumb length, strength, position, stability, mobility, sensitivity, and appearance.[14] Toe nail flap harvesting and transplantation for thumb reconstruction was firstly reported by Morrison in 1980 and successful, but 30% of the patients had foot dysfunction.[15] To overcome these disadvantages, computer-assisted design and 3D printing could provide novel options for individualized and precise hand surgery.[16-20] The advantages of these new technologies include: 1) precise positioning of surgical anatomy and location lesions; 2) preoperative simulation of operation and designing of surgical strategy; 3) intraoperative 3D real-time navigation; 4) determination of the extent of resection and surgical approach; and 5) simulation, teaching, and telemedicine.[21] These advantages are fully applicable to the reconstruction of thumb and finger defect.

3D printing technology could turn anatomical model from 2D to 3D, from plane to stereoscopy, and from static to dynamic. The preoperative observation of target site can be made by the surgeons to determine the optimal operation plan and the operation mode will eventually be changed from the traditional 'open-observe-operate' to 'observe-open-operate'.

The region of donor skin and soft tissue, and the size and length of bone can be accurately designed based on 3D-printed reconstructed model. The simulated reconstruction can be performed using a 3D medical software based on injured and healthy hands.[22] 3D printing improves the individualized and precise reconstruction strategy for thumb and finger defect and could decrease this risk because of better visualization and planning.

The good results in the present study were comparable to a study by Zang et al.[16] in five patients who underwent wrap-around flap design and second toe transplant to reconstruct a thumb. They showed excellent results in four patients and good results in one. Their success rate was 100%. Another study of four patients showed satisfactory reconstruction of the thumb using a donor toe after preoperative 3D-printed modeling of the surgical approach.[8] This study showed a success rate of 100% in 20 patients, with excellent or good appearance and function. These previous studies and ours suggest that this approach is promising for the planning of thumb reconstruction. Our conclusion is that based on rich experience and superb technique, digital preoperative planning and 3D printing can be used as an aid to reduce dependence on surgeons' experience and lower difficulty of some challenging operations. For example, size and shape of flap can be cut more accurately. Besides, side- injury of donor site can be reduced. From this aspect, 3D printing still has certain advantages in thumb reconstruction.

CONCLUSION

Our study is not without limitations. The number of patients was small and from a single center. There was no control group or randomization. Additional studies are necessary to determine the exact clinical value of this approach.

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