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.

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

INTRODUCTION

Thumb trauma can lead to dramatic effects on the functions of the hand, which 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. 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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medical education. 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.

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 IIa (proximal phalanx defect) and IIb (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.

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. 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 Cut with 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 make-ware 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.
Surgical considerations

The surgical mode was selected based on the thumb defect: 1) toe paraleum 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 hemi and metatarsosphalangeal joint, or reconstruction of the second toe and tendon tissue flap combined with metatarsosphalangeal joint reconstruction for IV° defect; and 5) reconstructing of contralateral second toe with the rhomboid dorsalis pedis flap and metatarsosphalangeal 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 paraleum 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 paraleum 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 Acta Ortop Bras. 2021;29(4):211-218 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 analyzed 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          | IIi                    | No                     | 42                            | 18                      | 17                                     |
| 4    | 2           | IIi                    | No                     | 22                            | 12                      | 12                                     |
| 5    | 34          | Ilb                    | Yes                    | 41                            | 16                      | 14                                     |
| 6    | 45          | Ilb                    | No                     | 37                            | 17                      | 15                                     |
| 7    | 28          | Ilb                    | Yes                    | 38                            | 17                      | 16                                     |
| 8    | 31          | Ilb                    | Yes                    | 31                            | 13                      | 12                                     |
| 9    | 44          | II                     | No                     | 32                            | 14                      | 14                                     |
| 10   | 27          | IIi                    | No                     | 33                            | 13                      | 13                                     |
| 11   | 11          | Ilb                    | Yes                    | 31                            | 14                      | 13                                     |
| 12   | 38          | Ilb                    | No                     | 41                            | 17                      | 15                                     |
| 13   | 39          | I                      | Yes                    | 35                            | 16                      | 14                                     |
| 14   | 41          | Ilb                    | No                     | 44                            | 17                      | 15                                     |
| 15   | 29          | Ilb                    | No                     | 46                            | 18                      | 16                                     |
| 16   | 30          | Ilb                    | Yes                    | 46                            | 17                      | 15                                     |
| 17   | 33          | II                     | No                     | 32                            | 14                      | 14                                     |
| 18   | 29          | Ilb                    | No                     | 37                            | 15                      | 13                                     |
| 19   | 27          | Ilb                    | Yes                    | 38                            | 16                      | 13                                     |
| 20   | 21          | Ilb                    | 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%).

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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          | Iib                             | 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                             | 0.9 (<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          | Iib                             | 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          | Iib                             | 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 | Follow-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 type, origin, route, and branches distribution. The whole picture of amputated thumb was created based on the other healthy hand through digital design, so the 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 foot in order to mark the blood vessels and incisions. B: Fabric design attached to donor foot. C: Dissociated left great toe.
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