Analysis of the Morphologic Differences of the Second Toe and Digits of the Hand, and Evaluation of Potential Surgical Intervention to Minimize the Differences Using Computer-Aided Design Technology

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Background: Toe "narrow neck" augmentation and pulp-plasty are two aesthetic surgical refinements that are performed to minimize the visual differences between the transferred toe and digit following a second toe–to-hand transfer. To improve the aesthetic refinements in a second toe transfer, the authors investigated the real shape of the flap and factors affecting the flap design using computer-aided design technology.
Methods: The plaster models of the right first through fourth digits and right second toes from 20 volunteers were scanned by spiral computer tomography to obtain three-dimensional reconstruction data. Computer-aided design software was used to analyze the data and simulate narrow neck augmentation and pulp-plasty. Next, the three-dimensional shapes of the transferred and excised flaps were created by Boolean calculation.
Results: The simulated transferred flaps were classified into two types in terms of their shape: crab claw and cross. The simulated excised pulp flaps could also be divided into two types—water drop and elliptic. There were individual variations and gender differences in the second toe morphology that resulted in different flap shapes. The flap shapes in narrow neck augmentation and pulp-plasty were determined using the location of the palmar protruding part and contour of the distal margin of the toe tip, respectively.
Conclusions: Accurate three-dimensional shapes of the flap could be obtained by computer-aided design, and there were individual variations and gender differences. The authors suggest that the affected factors should be considered, and computer-aided design could be used to improve the accuracy of flap design before surgery. (*Plast. Reconstr. Surg.* 134: 902e, 2014.)

Discrepancies between the second toe and digit are apparent. Although patients can restore considerable hand functions from second toe–to-hand transfer, some of them are unwilling to expose their hands publicly because of the unsightly appearance of the transferred second toe. Accordingly, various refinements, including "narrow neck" augmentation and pulp-plasty, have been implemented to minimize the morphologic differences and improve the aesthetic appearance of the reconstructed digits.[1–3] Narrow neck augmentation is used to improve the narrow appearance over the distal interphalangeal

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Fig. 1. Materials, tools, and plaster models. To make the second toe model, the metatarsophalangeal joint of the toe is passively flexed to 30 degrees; in addition, at the same time, the volunteer actively extends the interphalangeal joint to minimize the effect of the naturally bent joint of the toe on the research result.

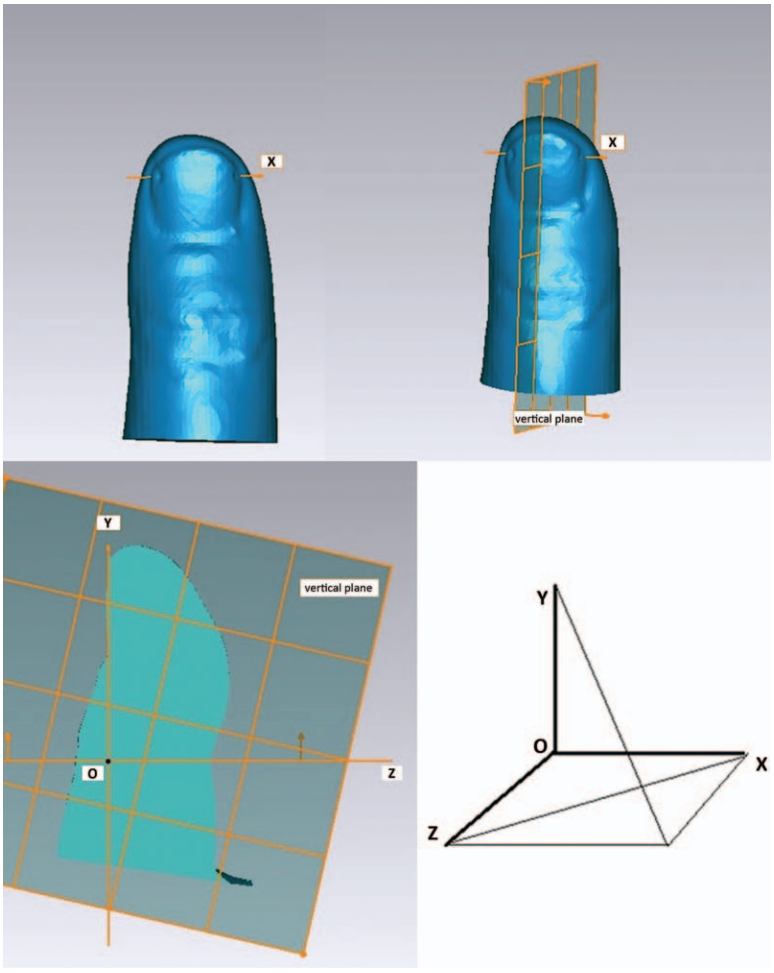

Fig. 2. Establishment of the coordinates for the digit/toe. (*Above*, *left*) *x* axis; (*above*, *right*) vertical plane; (*below*, *left*) *y* axis and *z* axis; (*below*, *right*) moving the *x* axis intersects the *y* axis and *z* axis at point *O*.

joint by releasing the narrow tissues and transferring the flap to cover the defect. Toe pulp-plasty reinvents the bulbous appearance of the toe tip by partially excising the pulp of the second toe.

In the literature, many different flap shapes have been reported for narrow neck augmentation, including strip, fusiform, keyhole, and four/eight-angle.[1] Longitudinal or bilateral oblique ellipse flaps have been designed for pulp-plasty.[2,4,5] However, it remains unclear why so many different flap shapes have been designed for the same purpose. We assumed the inconsistent flap design was attributable to individual morphologic variations of the digit and toe. Therefore, to improve the aesthetic refinements in second toe transfer, the relationship between the morphology of the toe/digit and flap shape was studied to identify the determining factors and relative rules in flap design that can aid hand surgeons in designing the flaps preoperatively.

Computer-aided design technology has been commonly used in clinical research to simulate operations, including orthognathic surgery[6] and cranioplasty.[7] In this study, computer-aided design was used to simulate narrow neck augmentation and pulp-plasty to create three-dimensional images of the flap.

PATIENTS AND METHODS

The study was approved by the Ethics Committee of Jishuitan Hospital. The morphologic data were obtained from 20 healthy adult volunteers with no history of hand or toe injuries and disease (10 men and 10 women; average age, 29.65

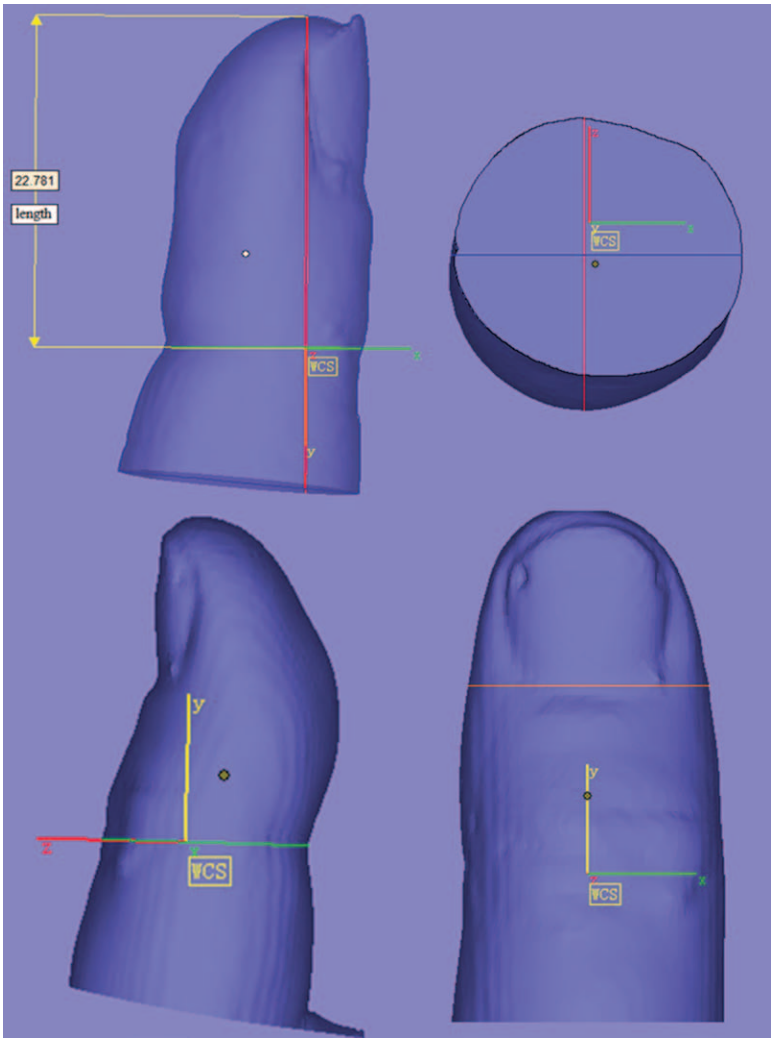

Fig. 3. Adjustment of the size of the digit. (*Above*, *left*) Length of the digit distal phalange; (*above*, *right*) width (*blue line*) and thickness (*red line*); (*below*, *left*) transverse plane at the level of the distal interphalangeal crease (*green line*); (*below*, *right*) transverse plane at the level of the proximal nail fold (*orange line*).

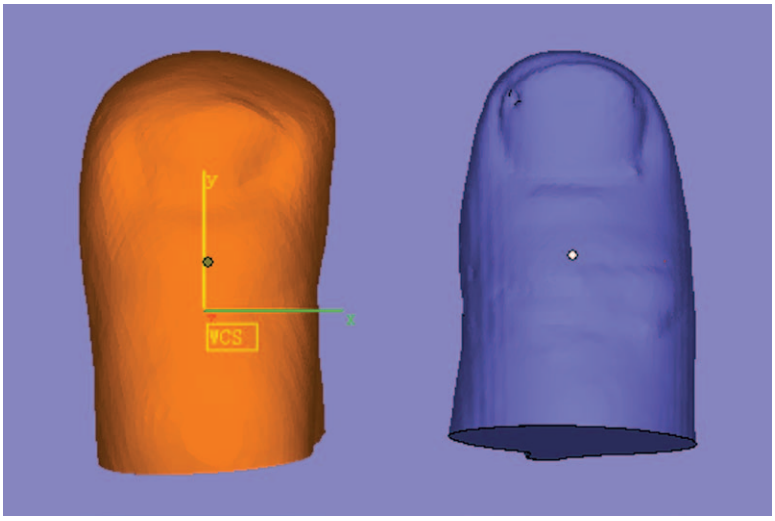

Fig. 4. Normal-sized second toe and rescaled thumb.

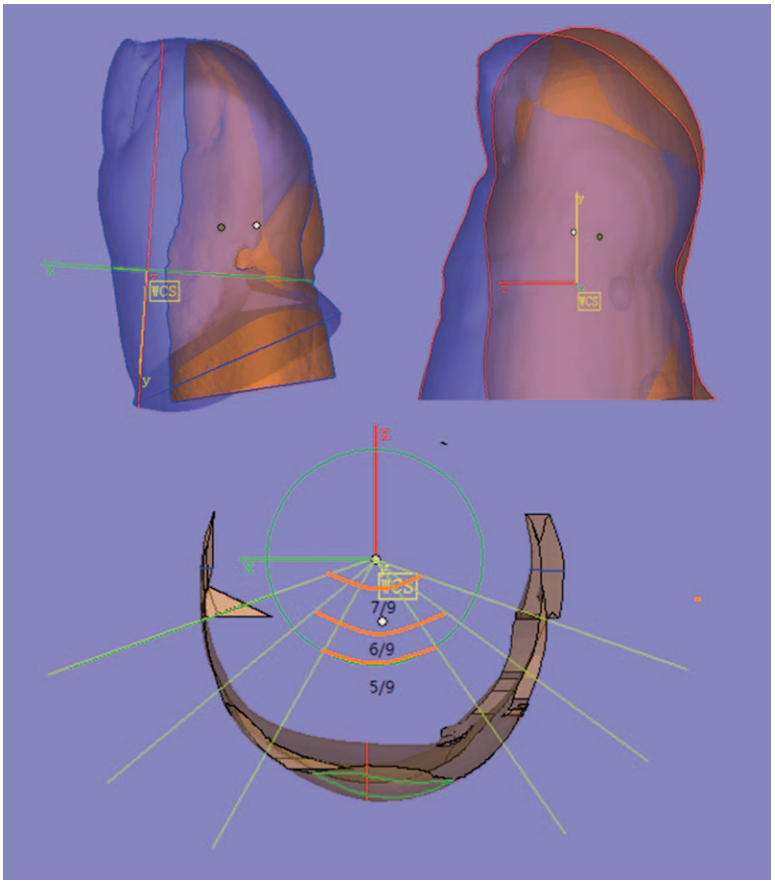

Fig. 5. Simulated toe narrow neck augmentation surgery and toe pulp-plasty. (*Above*, *left*) The outline of the toe and that of the thumb palmar, except the narrow neck region, substantially coincide; (*above*, *right*) the outline of the narrow neck portion of the toe and digit palmar substantially coincide; (*below*) the middle 5/9, 6/9, and 7/9 of the simulative flap is selected as the real transfer flap.

Video. Supplement Digital Content 1 demonstrates a simulated operation and flap design for narrow neck augmentation, available in the "Related Videos" section of the full-text article on PRSJournal.com or at ***http://links.lww.com/PRS/B156***.

years; range, 20 to 36 years). All of the volunteers signed the agreement and the informed consent forms. The average height of the male volunteers was 172.4 cm and that of the female volunteers was 163.5 cm. The average weight of the male volunteers was 73.2 kg and that of the female volunteers was 57.2 kg.

To avoid radiation exposure, plaster casts of the digits and toes of the volunteers were made and then scanned by computed tomography. We applied the impression techniques that are used in restorative dentistry to produce plaster casts of the first through fourth digits of the right hands, and the second toes of the right feet (Fig. 1).[8] The plaster models were scanned using a 64-slice spiral computed tomography system (Aquilion 64; Toshiba, Tokyo, Japan), with a slice thickness 0.5 mm, to obtain computed tomographic data. The data were stored in the Digital Imaging and Communications in Medicine format and imported to Mimics 10.01 software (Materialise Corp., Leuven, Belgium) to create three-dimensional images in the Standard Tessellation Language format.

Establishing Coordinates for the Digit/Toe

To create three-dimensional coordinates of the digit/toe, Standard Tessellation Language data were imported to Geomagic Studio 10.0 software (Geomagic Corp., Research Triangle Park, N.C.). The connecting line between the bilateral vertexes of the

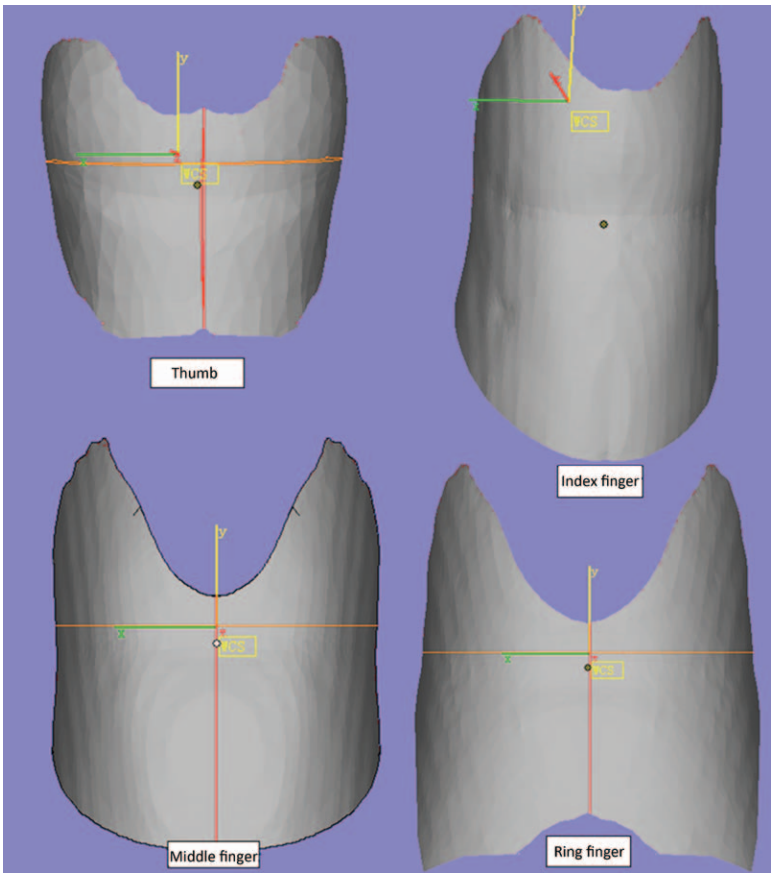

Fig. 6. Type I simulated transfer flap of the first through fourth digits.

nail groove was set as the *x* axis (Fig. 2, *above*, *left*). The plane that was perpendicular to the *x* axis and passed through the midpoint of the two vertexes was set as the sagittal plane (Fig. 2, *above*, *right*). The line connecting the free margin of the nail plate and proximal nail fold was set as the *y* axis. On the sagittal plane, the line perpendicular to the *y* axis and passing through the distal interphalangeal crease was set as the *z* axis (Fig. 2, *below*, *left*). Finally, the *x* axis was moved to the intersection point (point O) of the *y* axis and *z* axis to form the three-dimensional coordinate system (Fig. 2, *below*, *right*).

Surgery Simulation and Flap Design

The three-dimensional models of the digit/toe were imported into Magics 18.0 (Materialise). Point O of the digit/toe was coincided to construct two models at the same coordinate.

Narrow Neck Augmentation

First, the size of the digit distal phalanx was adjusted by changing its length, width, and thickness (transverse plane at the level of the distal interphalangeal crease) until it was equal to that of the second toe (Figs. 3 and 4). Next, the digit was moved along the *z* axis until its palmar outline, except the narrow neck region, substantially coincided with that of the toe (Fig. 5, *above*, *left*). Nonoverlapped three-dimensional images considered as blueprints of the transfer flaps were created after removing the overlapped three-dimensional images by Boolean calculation. (**See Video, Supplemental Digital Content 1**, which demonstrates a simulated operation and flap design for narrow neck augmentation, available in the "Related Videos" section of the full-text article on PRSJournal.com or at ***http://links.lww.com/PRS/B156.***) In the actual operation, the lateral portion of the "narrow neck" was corrected by releasing the local tissue, and only the central part of the neck was augmented by the flap. Thus, we divided the blueprint into nine equal parts, and considered the middle 5/9, 6/9, and 7/9 as the real flaps in our experience (Fig. 5, *below*).

Pulp-Plasty

The adjustment of the size of the digit was similar to the above procedure. The difference was that the width and thickness were adjusted at the level of the proximal nail fold rather than the level of the distal interphalangeal crease (Fig. 3, *below*, *right*). The digit

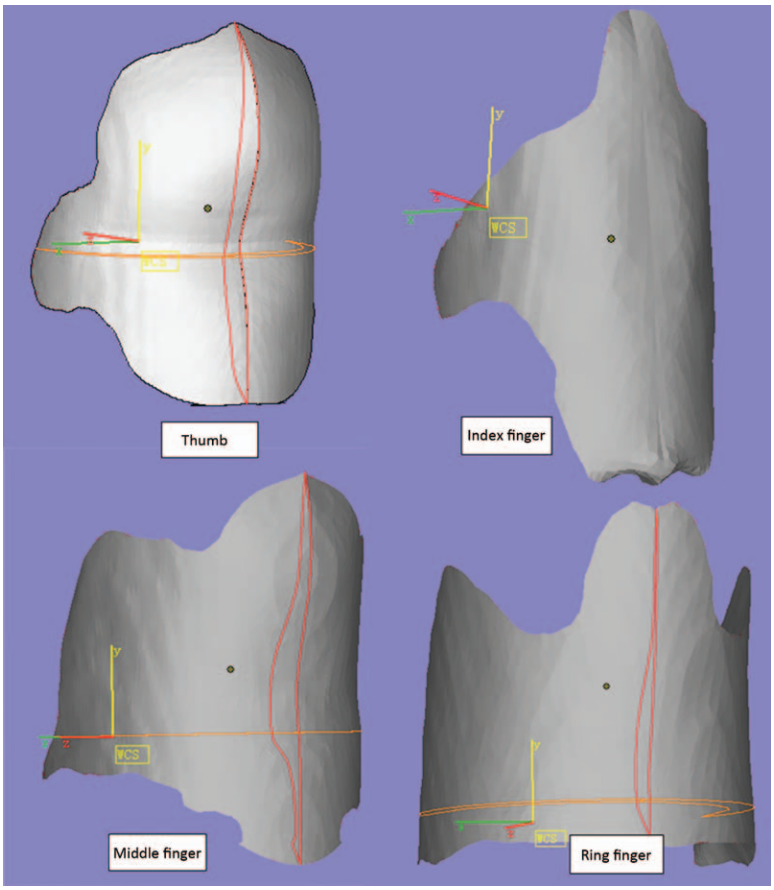

Fig. 7. Type II simulated transfer flap of the first through fourth digits.

was then moved along the *z* axis until the outline of the narrow neck of the toe and digit substantially coincided (Fig. 5, *above*, *right*). Boolean calculation was performed to remove the overlapped three-dimensional image, and the remaining image was the flap that should be removed during pulp-plasty.

RESULTS

Simulated Narrow Neck Augmentation Surgery

First, the shape of the transferred flap could be classified into two types. In type I, crab claw shape, the flap was concave in the middle and protruding on both sides (Fig. 6). In type II, cross shape, the flap was protruding in four directions (Fig. 7). The shapes of the flap were related to the location of the protruding part of the pulp of the toe (Fig. 8, *above*). If the protruding part was located lower, the flap was crab claw shaped (type I). By contrast, the flap was cross shaped (type II) if the protruding part was located higher.

Second, in type I, the flap for thumb reconstruction was shorter than that for the index, middle, or ring finger. In type II, the flap for thumb reconstruction was shorter than that for each of the other fingers, with a wider central part and narrower lateral protrusion.

Third, in most of the volunteers, the flaps for the thumb, index, middle, and ring fingers were the same type. In one female volunteer only, the flaps for the thumb and index fingers were type II, whereas those for the middle and ring fingers were type I. In the latter case, the tips of the index finger and thumb were pointed, whereas those of the middle and ring fingers were obtuse. Fourth, in female volunteers, most of the flaps were type I; however, in men, most of the flaps were type II (Table 1).

Fifth, the flap shape did not change much after side cutting. Only the width of the flap changed. In some exceptional cases, the flap for thumb reconstruction changed from a cross (type II) into an elliptical shape after being narrowed to the 5/9 area.

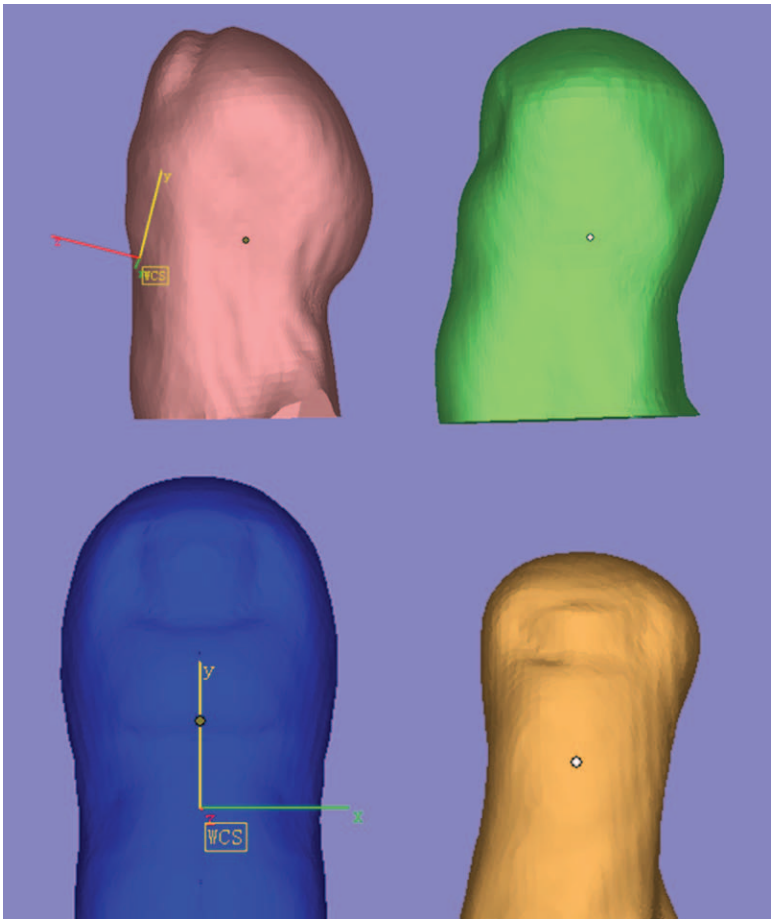

Fig. 8. Flap shapes related to the outline of the second toe. (*Above*) Flap shapes related to the location of the protruding part of the pulp of toe for toe narrow neck augmentation surgery. (*Below*) Flap shapes related to the contour of the distal margin of the toe tip for toe pulp-plasty.

Table 1. Type I and Type II Flaps in Toe Narrow Neck Augmentation Simulated Surgery

	Thumb	Index Finger	Middle Finger	Ring Finger	Total
Type I					
Male	2	2	2	2	8
Female	7	7	8	8	30
Type II					
Male	8	8	8	8	32
Female	3	3	2	2	10

Simulated Pulp-Plasty

First, the flap to be removed could also be classified into two types (Fig. 9). Type I (water drop shape) was a flap with a broader distal end, and type II was a flap with an elliptical shape. The flap shape was related to the contour of the distal margin of the toe tip. When the second toe tip was more "boxy," the flap belonged to type I (Fig. 8, *below*).

Second, within the same type, the flaps for the index, middle, and ring fingers were similar to that for the thumb. Third, in all of the volunteers, the excised pulp flaps of first through fourth digits were the same type. Finally, there were more type I flaps than type II flaps. In all of the female volunteers, the flaps were type I (Table 2).

CASE REPORTS

Case 1

A 24-year-old female volunteer presented with a higher location of the protruding part of the pulp of the second toe. After simulation of narrow neck augmentation surgery, the simulated flap was type II. (**See Video, Supplemental Digital Content 1**, ***http://links.lww.com/PRS/B156***.)

Case 2

A 33-year-old male volunteer presented whose second toe tip was not boxy. First, the size of the digit distal phalanx was adjusted to be equal to that of the second toe. Next, the digit was moved along the *z* axis until the outline of the narrow neck of the toe and digit substantially coincided (Fig. 5, *above*, *right*). After Boolean calculation, the nonoverlapped three-dimensional image was considered the simulated excised flap. It was type II because of the elliptical shape (Fig. 10).

DISCUSSION

The function restored by toe-to-hand transplantation is satisfactory[1,9]; however, the obvious visual differences between the normal digit and the reconstructed digit present a vexing cosmetic problem.[2,3] Among the differences between the second toe and digit, the bulb-like tip and narrow neck deformities are major issues. In thumb reconstruction, these differences are more obvious.[3]

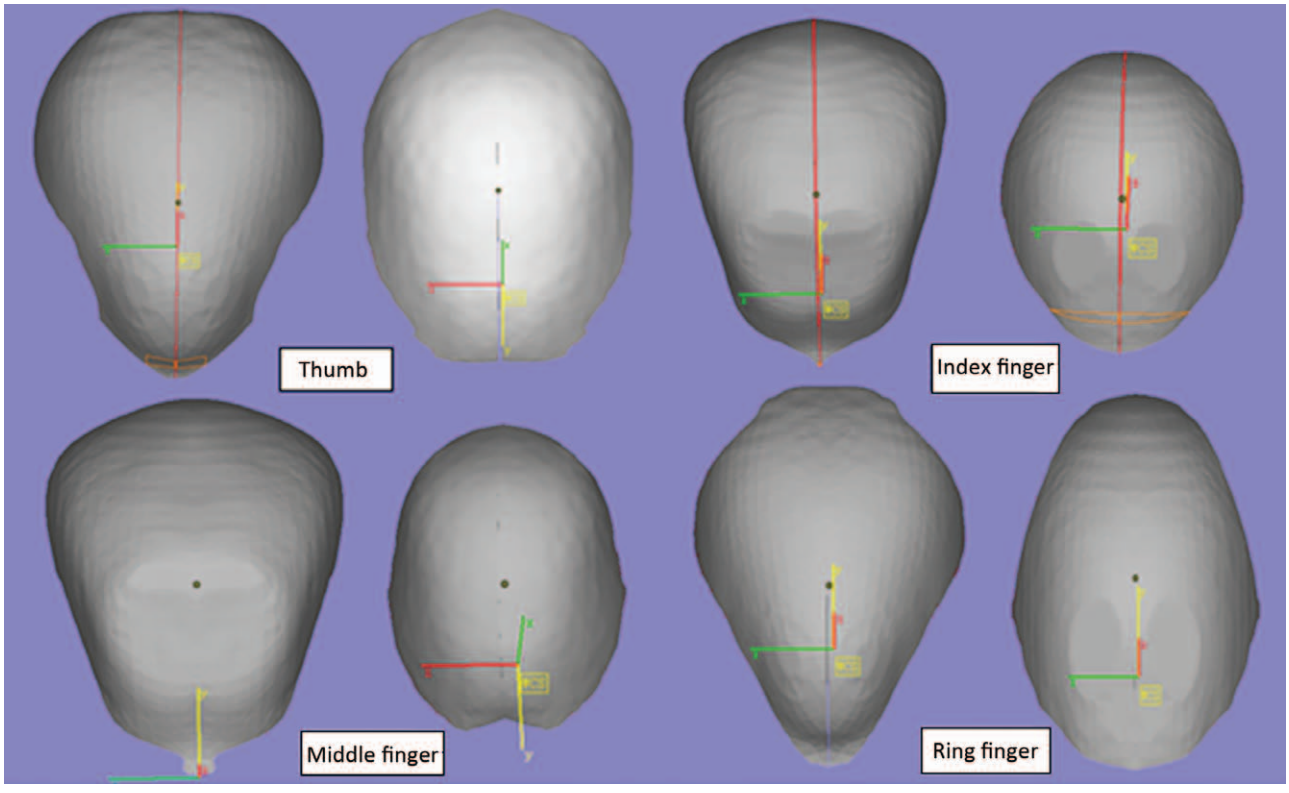

Fig. 9. Simulated excised pulp flap of the first through fourth digits.

Table 2. Type I and Type II Flaps in Simulated Toe Pulp-Plasty

	Thumb	Index Finger	Middle Finger	Ring Finger	Total
Type I					
Male	5	5	5	5	20
Female	10	10	10	10	40
Type II					
Male	5	5	5	5	20
Female	0	0	0	0	0

Narrow neck augmentation and pulp-plasty have been used to address those issues after toe-to-hand transplantation, and the results have been satisfactory. Nevertheless, the shapes of the flap in the literature have varied (Table 3).[5,10–18]

Computer-aided design technology is a new method for preoperative planning to visualize accurate morphologic variations between preoperatively and postoperatively. Based on the visible three-dimensional variations, surgeons can design the implant and construct three-dimensional plans of osteotomy using computer-aided design software.[6,7] In this study, we attempted to use computer-aided design to simulate narrow neck augmentation and pulp-plasty, and found that the rules of the flap design were based on the morphologic differences between the digits and second toes.

The methods and software used in our study are precise and reliable because they have been applied in clinical research for virtual surgery simulation and measurement of the volume and dimensions of various body organs with good results.[19–21] To reveal the morphologic differences, the sizes of the digits and second toe were equalized in three dimensions. Thus, the disparities between the digit and toe pulp (i.e., the plantar contour changes before and after surgery) could be clearly visualized. The flap shapes could be determined by simulation.

We found that both the transferred and excised flaps could be classified into two types. The shape of the flap was affected by many factors; among them, the contour of the second toe played a critical role and should be evaluated carefully before surgery.

In the simulated narrow neck augmentation operations, the flap type accorded with the location of the protruding tissues, indicating that the location of the protruding part determined the shape and size of the narrow neck region of the second toe. When the protruding part was located higher, the narrow region was longer and required more distal augmentation. Both flap types had relatively complex shapes. The surgeon may be concerned that the flap design might compromise the blood supply of the flap and the transferred toe. However, according to previous reports, the survival rate of a transferred flap was high despite its complex shape design (Table 3). For example, the survival rate of the polygonal flap was 100 percent.[17] No report has shown that the complex flap transfer can jeopardize the vascularity of the second toe.[10–18] However, clinical situations are more complex; thus, the vascularity of the flap and reconstructed digit must be considered, and the

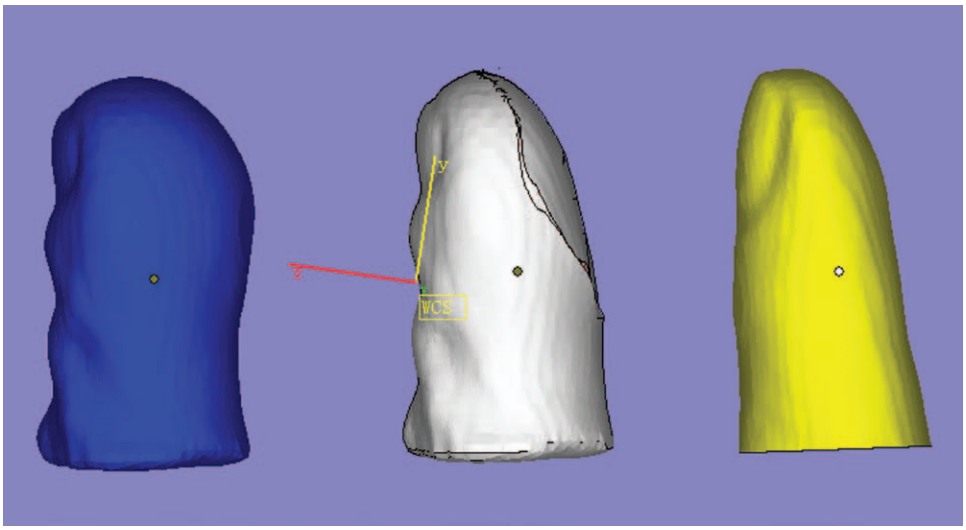

Fig. 10. Comparative three-dimensional models for simulated toe pulp-plasty. (*Left*) Preoperative second toe; (*center*) simulated post-plasty for the second toe; (*right*) simulated post-plasty for the index finger.

Table 3. Review of Toe Narrow Neck Augmentation Surgery

	Pan et al.[10]	Wang et al.[11]	Wang et al.[12]	Wang et al.[13]	Wang et al.[14]	Zhang et al.[15]	Zhao et al.[5]	Huang et al.[16]	Wei et al.[17]	Liu et al.[18]
Year of publication	2002	2006	2006	2002	2008	2008	2010	2011	2010	2010
Follow-up time, mo	2–10	3–24	6–24	3–24	1–24	6–36	6–36	3–24	3–12	3–6
No. of transferred toes	12	6	9	46	13	48	6	8	11	10
Shape of transfer flap	Fusiform	Rhomboid	Ellipse	Fusiform	T-shape ($n = 6$); H-shape ($n = 7$)	Strip	Keyhole	T-shape	Polygonal	Fusiform
Donor site of transfer flap										
Flap from the fibular side of the great toe	+	–	–	+	+	+	+	+	+	–
Dorsal index finger flap	–	–	+	–	–	+	–	–	–	–
Flap from the proximal plantar side and wedged of the second toe	–	+	–	–	–	–	–	–	–	–
Tibial digital artery flap from the third toe	–	–	–	–	–	–	–	–	–	+
Vascular crisis of transfer flap	0	0	2	0	1	0	0	0	0	0
Flap necrosis	0	0	0	0	0	0	1 case partial	0	0	0
One-stage plasty	+	+	–	+	+	+	+	+	+	+
Two-stage plasty	–	–	+	–	–	–	–	–	–	–
Patient satisfaction	Good	Good	Good	Good	Good	8 cases Unsatisfactory	1 case Unsatisfactory	Good	Good	Good

+, yes; –, no.

reliability of the simulated flap design needs to be verified by clinical application.

In simulated pulp-plasty, the flap was determined by the contour of the distal margin of the toe tip. When the second toe tip was more boxy, more tissue of the two distal sides was required to be removed, making the second toe tip more curved and smooth, like digits. In the actual operation, the type I flap may be difficult to harvest by a single excision. However, removal of a bilateral oblique elliptical flap combined with a longitudinal elliptical flap can have the same effect.

Other factors, such as the pulp shape of the fingertip, also affected the flap shape, particularly in the simulated narrow neck augmentation operations. The transferred flap types for different digits in one volunteer were different, indicating the morphologic inconsistency of the digits. However, clinically, the inconsistency could be ignored because the original template was missed unless bilateral symmetry was required by patients. Importantly, for neck augmentation, a stout transferred flap is required for the thumb compared with those for the other digits. For pulp-plasty, the flaps for different digits were relatively uniform. In addition, this study showed that there were different proportions of male and female volunteers regarding flap type, indicating the morphologic difference of the second toe between men and women.

Based on our findings, the following observations regarding flap design are presented: (1) for toe narrow neck augmentation surgery, a type I flap should be used if the protruding part of the second toe pulp is lower, and vice versa for type II; (2) for toe pulp-plasty, a type I flap should be used if the shape of the second toe is more boxy, and vice versa for type II; (3) most the flaps of the thumb, index, middle, and ring fingers are the same type. Considering the large individual differences, if the requirements of the patients are higher, presurgery computer-aided design should be performed on a case-by-case basis.

This study has several limitations. The modeling process was time consuming and required knowledge of certain computer and operating techniques. Simplification of data collection and integration of the processing program are long-term development directions. In addition, for the actual preoperative design, other factors should be considered because of the complexity of the technique (i.e., the occurrence of postoperative scarring and skin shrinkage). This flap design method needs the support of clinical application and correction, which will be the goal of our future study.

CONCLUSIONS

Using computer-aided design technology, we successfully simulated two commonly applied refinement procedures after toe-to-hand reconstruction, and the flaps to be transferred or removed that were required for revision were clearly visualized. There were individual variations and gender differences of second toe morphology, resulting in different flap shapes. The location of the palmar protruding part and contour of the distal margin of toe tip, respectively, determined the flap shape in narrow neck augmentation and pulp plasty. We suggest careful consideration of the above individual variations before surgery and using computer-aided design to obtain more accurate flap design.

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