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Research Article

One-stage reconstruction of four fingers in children using microsurgical autotransplantation of foot tissue complexes

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ABSTRACT

BACKGROUND: Toe-to-hand transfer is still the most promising and relevant method for restoring fingers that are missing from birth or after injury. In cases requiring the restoration of two or more digits, simultaneous transplantation of tissue complexes from both feet, including one or two toes, is possible and necessary. Thus, a maximum of four fingers can be restored during one operation, Such operations, according to the literature, are performed extremely rarely because they are very extensive and time-consuming.

AIM: To present the results of simultaneous microsurgical autotransplantation of four toes to the hand in children with congenital and acquired pathologies.

MATERIALS AND METHODS: The study used clinical, radiological, and biomechanical methods to assess the results of nine patients with congenital and acquired upper limb deformities who underwent simultaneous microsurgical autotransplantation of two tissue complexes from each foot, including toes II–III. The indications for performing this method of microsurgical reconstruction in children with the absence of four (or all five) fingers have been determined. The results, postoperative complications, and conditions of the donor and recipient zones were analyzed.

RESULTS: To date, 914 such operations have been perfomed in children. In nine cases, four toes were simultaneously transplanted (two from each foot). The average age of the patients was 4.2 years. Two children had congenital malformations of the hand, and seven had consequences of trauma. In eight cases, fingers II–V were restored, and in one case, fingers I–IV were restored. Complications associated with impaired blood circulation in the grafts were observed in 22% of the cases; however, they were temporary. All transplanted grafts survived. All patients required continued surgical treatment after the toe transfer to improve their appearance and function. Biomechanical examination methods showed complete restoration of function on average of 4 months (±1 month) after surgery.

CONCLUSIONS: This study showed the possibility and effectiveness of using toes for hand transfer in children with both congenital and acquired hand pathologies that require the restoration of four fingers. Simultaneous microsurgical transplantation of toes ensures the restoration of a good appearance of the hand and its functionality.

Keywords: microsurgical autotransplantation; toe-to-hand transfer; congenital hand deformity; consequence of injury; hand surgery; finger reconstruction; children.

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Научная статья

Одноэтапное восстановление 4 пальцев кисти у детей методом микрохирургической аутотрансплантации комплексов тканей стоп

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АННОТАЦИЯ

Актуальность. По-прежнему наиболее перспективным и актуальным методом восстановления отсутствующих с рождения или после травмы пальцев кисти является микрохирургическая аутотрансплантация пальцев стоп. В случаях необходимости восстановления 2 и более пальцев возможна и необходима одновременная пересадка комплексов тканей с обеих стоп, включающих 1 или 2 пальца. Таким образом, в ходе одной операции возможно произвести реконструкцию максимально 4 пальцев кисти. Такие операции, по данным литературы, производятся крайне редко, поскольку являются очень трудоемкими и длительными.

Цель — представить результаты опыта одномоментной микрохирургической аутотрансплантации 4 пальцев стоп на кисть у детей с врожденной и приобретенной патологией.

Материалы и методы. С помощью клинического, рентгенологического, биомеханического методов проведена оценка результатов лечения 9 пациентов с врожденными и приобретенными деформациями верхней конечности, которым была выполнена одномоментная микрохирургическая аутотрансплантация двух комплексов тканей с каждой стопы, включающих II–III пальцы. Определены показания к выполнению данного метода микрохирургической реконструкции у детей с отсутствием 4 (или всех 5) пальцев кисти, проведен анализ результатов, послеоперационных осложнений, оценка состояния донорской и реципиентной зон.

Результаты. Из 914 аутотрансплантаций пальцев стоп на кисть у детей, произведенных в отделении реконструктивной микрохирургии и хирургии кисти, в 9 случаях произведена одномоментная пересадка 4 пальцев (с каждой стопы по два). Средний возраст пациентов составил 4,2 года. Два ребенка были с врожденными пороками развития кисти и 7 — с последствиями травмы. В 8 случаях производили восстановление II–V пальцев кисти и в одном случае — I–IV пальцев. Осложнения, связанные с нарушением кровообращения в трансплантатах, наблюдали в 22 %, но они были временными. Все пересаженные трансплантаты прижились. Всем пациентам потребовалось продолжение хирургического лечения после пересадки пальцев с целью улучшения их внешнего вида и функции. Биомеханические методы обследования показали полное восстановление их функции в среднем через 4 мес. (±1 мес.) после операции.

Заключение. Проведенное исследование показало возможности и эффективность применения данной операции у детей как с врожденной, так и с приобретенной патологией кисти при необходимости восстановления 4 пальцев. Одномоментная микрохирургическая пересадка пальцев стоп обеспечивает восстановление хорошего внешнего вида кисти и ее функциональных возможностей.

Ключевые слова: микрохирургическая аутотрансплантация; пересадка пальцев; врожденная деформация кисти; последствие травмы; хирургия кисти; восстановление пальцев; дети.

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Research Article

通过显微外科自体移植足部组织复合物，分阶段修复儿童手部的4个手指

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摘要

论证。目前足趾显微外科自体移植仍然是修复出生后或外伤后缺失手指的最有前途和最实用的方法。在需要修复2个或更多足趾的情况下，同时移植双脚的组织复合物（包括1个或2个足趾）是可能的，也是必要的。因此，在一次手术过程中最多可以重建手部的4个手指。根据文献记载，这种手术很少进行，因为手术非常耗费人力和时间。

目的。本研究旨在展示在先天性和后天性病变的儿童中，通过显微外科手术将4个足足趾自体移植到手部的经验成果。

材料和方法。通过临床、X线、生物力学等方法，对9例先天性和后天性上肢畸形患者进行一次显微外科自体移植，每足2个组织复合体累及II~III指的治疗结果进行评价。确定了对手部缺失四指（或全部五指）的儿童实施这种显微外科重建方法的适应症；分析了结果、术后并发症以及对供体和受体区域的评估。

结果。在修复显微外科和手外科进行的914例儿童手部足趾自体移植手术中，9例进行了4个足趾（每个脚两个）的单阶段移植。患者的平均年龄为4.2岁。两名患儿的手部有先天性畸形，7名患儿的手部有外伤。8例手部II~V指修复，1例手部I~IV指修复。22%的移植物出现了与循环障碍相关的并发症，但这些并发症都是暂时的。所有移植的移植物都存活了下来。所有患者在手指移植后都需要继续接受手术治疗，以改善外观和功能。生物力学检查方法显示，他们在术后平均4个月（±1个月）就完全恢复了功能。

结论。这项研究表明，对于患有先天性和后天性手部病变的儿童，在需要恢复4个足趾时，使用这种手术的可能性和有效性都很高。一次显微外科足趾移植手术可恢复手部的良好外观和功能。

关键词：显微外科自体手指移植；手指移植；先天性手部畸形；创伤后遗症；手部手术；手指重建；儿童。

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BACKGROUND

Finger reconstruction in children is a complex and critical issue in orthopedics and traumatology and involves surgical treatment for congenital underdevelopment and posttraumatic deformities of the fingers. Surgeons have been exploring optimal solutions to restore fingers, including various surgical methods and prosthetics. Surgical magnifying optics and microsurgical technologies have greatly increased the treatment options available for patients with musculoskeletal pathologies. The use of a surgical microscope has enabled the suturing of small structures such as vessels and nerves. This technique has been used to restore blood flow to segments severed by trauma and for replantation. Furthermore, these technologies are crucial for the transplantation of blood-supplied tissue complexes to restore blood circulation after being moved to the recipient zone. Currently, several researchers and leading hand surgery experts recognize that the microsurgical autograft method of toe-to-hand transfer is the optimal and most effective method for finger reconstruction. This surgical treatment method is the only method that can restore the fingers of the hand to a structure and function that is most similar to the original. Stable functional results and subsequent growth and development of the operated limb should be achieved in this patient group [1–3].

In cases where several fingers are missing, surgeons have developed methods for one-stage transplantation of two toes from one foot (block of 2–3 toes) or transplantation of one autograft from each foot [4–6]. The graft can include one or two toes of the foot on a common vascular pedicle. If several fingers should be created, autografts from the feet are transplanted in 2–3 surgeries. Following finger restoration, 2–3 additional surgeries are required for skin and tendon-plastic procedures to improve hand appearance and function. Finger restoration typically involves multiple stages. Thus, the treatment process can span several years.

Autotransplantation of toes carries a risk of complications, particularly those related to microcirculation, which can result in persistent circulatory disorders and transplanted autograft necrosis. Numerous studies, including those conducted at our institution, have addressed this issue. Effective management of complications following microsurgery is critical in determining the success of the intended treatment [7, 8].

A significant disadvantage of this method is the use of a healthy foot as a donor area. However, long-term observations have shown that patients are satisfied with the cosmetic and functional condition of the donor area and experience no pain and that foot reconstruction does not affect their quality of life [9, 10].

Studies in foreign and Russian literature regarding the one-stage restoration of the four fingers of the hand using the toe-to-hand method are limited. Therefore, the present study using this treatment method in children is significant.

This study aimed to present the results of one-stage microsurgical autotransplantation of four toes to the hand in children with congenital and acquired pathologies.

MATERIALS AND METHODS

The treatment results of nine pediatric patients with congenital and acquired upper limb deformities were analyzed. The patients underwent one-stage microsurgical autotransplantation of two tissue complexes from each foot, including toes 2–3, to restore four fingers of the hand. This study investigated the indications for performing microsurgical reconstruction in children missing four (or all five) fingers of the hand and evaluated the results, postoperative complications, and donor and recipient areas.

Since 1986, the Department of Reconstructive Microsurgery and Hand Surgery at the Turner National Medical Research Center for Pediatric Traumatology and Orthopedics has performed 914 autotransplants of toes to replace fingers on the hand. Only 1% of these surgeries (nine cases) required a one-stage restoration of four fingers using transplantation of two blocks of toes 2–3. Eight cases involved reconstruction of the "long" (triphalangeal) fingers, whereas in one case, the toes were repositioned to the location of fingers 1–4. The children's mean age was 4.2 years, with the youngest patient being 2.3 years and the oldest 8.4 years. Two children had congenital hand malformations and seven experienced trauma. The gender distribution of operated children was similar (boys, 5; girls, 4). Table 1 shows the etiologic factors responsible for the presence of congenital or acquired hand pathology. All children underwent pre- and postoperative examinations, including clinical, radiological, and biomechanical tests.

The parents of the children were informed about the disadvantages, risks, and potential postoperative complications of microsurgical autotransplantation of the toes to the hand before discussing the surgical intervention. Moreover, possible alternative surgical techniques and prostheses were considered. Ultimately, the decision to perform autotransplantation of the toes to the hand was made by the parents in all cases.

Clinical examination comprised collecting the patient medical history and conducting a classical orthopedic examination. Data obtained from parents included pregnancy details, ultrasound findings (if available), and the timing of delivery. In cases of trauma, we clarified the nature and circumstances of the injury, the timing and method of primary surgical treatment, and subsequent stages of treatment before admission to our hospital.

Furthermore, clinical examination evaluated the separation of the fingers (underdevelopment), condition of the preserved fingers, hand functional capabilities (including the presence and types of grasping) of the hand, skin condition (including the prevalence and degree of scarring), and consequences of damage to the preserved anatomical

Table. Characteristics of the clinical materials

Таблица. Характеристика клинического материала

Sex	Age (years)	Etiologic factor		Recipient area	
		congenital pathology	post-traumatic pathology	II–V fingers	I–IV fingers
Boys	2	–	Meat grinder	+	–
	3	Ectrodactylia	–	+	–
	5	–	Meat grinder	–	+
	5	–	Burn	+	–
	8	–	Firecracker	+	–
Girls	2	Ectrodactylia	–	+	–
	4	–	Meat grinder	+	–
	4	–	Meat grinder	+	–
	5	–	Meat grinder	+	–

structures of the hand. Further, the extent of passive and active movements in the preserved joints was measured, and the condition and function of the forearm and hand muscles were evaluated. Additionally, the aesthetic appearance of the hand was assessed and potential methods for improvement were determined.

X-ray examinations were performed to identify characteristic changes in the bones and joints of the injured (underdeveloped) hand and fingers. Radiographs of the hand were taken in two projections (dorsolateral and straight for the first finger) upon admission to the hospital, intraoperatively, before the removal of fixation spokes, and at subsequent stages of surgical treatment of children.

The analysis focused on the shape and size of the short tubular bones that remained after trauma and the presence of metacarpophalangeal joints and signs of associated lesions.

This study examined the biomechanics of children's feet before and after toe-to-hand transfer, focusing on static and kinematic assessments. A plantographic study was performed to determine the range of normal foot parameters by calculating the confidence limits of the arithmetic mean (M – L...M + L) and comparing possible deviations of the corresponding parameters in operated patients, assess statistical validity, and identify any possible concomitant deviations from the normal plantographic characteristics of the feet. A stabilometric study was conducted to assess the functional abilities of the lower extremities following toe transplantation.

The results were statistically processed using parametric and nonparametric methods in Statistica v.13.3.

After the examination, microsurgery was performed. Typically, two teams of surgeons work simultaneously to promptly conduct the procedure.

Surgery. An incision was made along the dorsal surface of the foot in the projection of the second tarsal interspace, continuing to the plantar surface through the first and third finger interspaces. The large and small saphenous veins that contribute to the blood circulation of toes 2–3 were isolated. The dorsal artery of the foot and its continuation as the first dorsal metatarsal artery were mobilized from the proximal part of the foot. Then, the structures on the plantar surface of the foot were isolated. These structures included a fragment of the arterial plantar arch and three metatarsal plantar arteries that anastomose with the first dorsal metatarsal artery through a deep arterial branch. The goal was to preserve the maximum number of arteries and venous branches for the graft. The flexor and extensor tendons of toes 2–3 and the plantar toe nerves were isolated and crossed as proximally as possible. Capsulotomy of metatarsophalangeal joints 2–3 was performed (in two cases by osteotomy of the metatarsal bones), and the toes were separated from the donor bed.

The toes on the second foot were similarly isolated. The variant vascular anatomy was found to be identical in 78% of cases in both feet.

Incisions were made in the recipient area, specifically on the preserved fragments (stumps) of the main phalanges of fingers 2–5, with continuation on the dorsal and palm surfaces of the hand. The extensor tendons of fingers 2–5 and the venous branch of the *v. basilica* were identified on the dorsal surface of the hand. The tendons of the flexors of fingers 2–5 and the common finger nerves were mobilized on the palmar surface of the hand. An additional angular incision in the area of the "anatomical snuffbox" allowed for the detection of the radial artery and branches of the *v. cephalica*. The ulnar artery or its continuation, the palmar arterial arch with the common palmar finger arteries, could also be used as a recipient artery for feeding. If preserved, the bone stumps of the phalanges of fingers 2–5 were exposed and freed from scars.

After removing the feeding legs of the grafts on the feet, they were transplanted to fingers 2–5 of the hand and secured with spokes along the axis. Then, the flexor and extensor tendons and finger nerves were sutured individually. End-to-end microvascular anastomoses were performed between the arteries of the donor and recipient regions and

between the veins of the hand and grafts. The microvascular clips were then removed to assess the adequacy of blood circulation in the transplanted autografts. The skin wounds were sutured layer by layer. If defects in the wounds were observed, combined skin plasty was performed using thick split autografts. Finally, aseptic dressings and plaster casts were applied to the upper and lower extremities.

During the postoperative period, the limbs that were operated on were kept elevated to reduce edema. Moreover, anticoagulant therapy was administered for the first 3–4 days to prevent microcirculatory complications [7].

The postoperative sutures were removed 2 weeks after surgery, and the fingers were fixed with spokes for 5–6 weeks. Following X-ray control, the spokes were removed, and conservative treatment methods were initiated. Six months later, the children were admitted for further surgical treatment, which included skin plastic surgeries and tendon release from scars to improve the hand's cosmetic and functional state.

The treatment outcomes were assessed following the final surgeries that involved a combination of skin grafting to enhance the shape and contours of the fingers and deepen the spaces between the fingers. In 7 of 9 cases, the final operation after skin plasty was tenolysis of the finger flexor and extensor tendons. These tendons often adhere to postoperative scars. After each stage of surgical treatment, the children underwent rehabilitation that included physical therapy, massage, warming procedures (e.g., ozokerite or paraffin), and physiotherapy aimed at controlling scars.

The study used a modified version of the visual analog scale (VAS) to assess the cosmetic outcome and overall satisfaction of both patients and their parents with the treatment. The VAS (Fig. 2) is a horizontal line representing the range of patient satisfaction with the cosmetic condition of the hand. The patient or parents were asked to evaluate the esthetic condition of the treatment and indicate their level of satisfaction on a scale from 0 to 10 (0, complete dissatisfaction with the cosmetic result; 10, complete satisfaction). The distance between the marks on the scale was measured in centimeters and rounded if required. The evaluation was conducted by both patients and parents and the specialist (doctor). The results were assessed on a scale of 0–2 for unsatisfactory, 3–5 for satisfactory, 6–8 for good, and 9–10 for excellent.

The assessment of treatment outcomes included determining six basic types of grip (cylindrical, globular, flat, pinch, hook, and interfinger) and conducting a questionnaire survey of patients and parents. The ABILHAND-Kids questionnaire served as the prototype, containing 21 questions directly related to the patient's daily activities. Parents were asked to rate their child's performance for each action, with the following answer options: "Impossible to perform," "Difficult," "Easy," and "Difficult to answer."

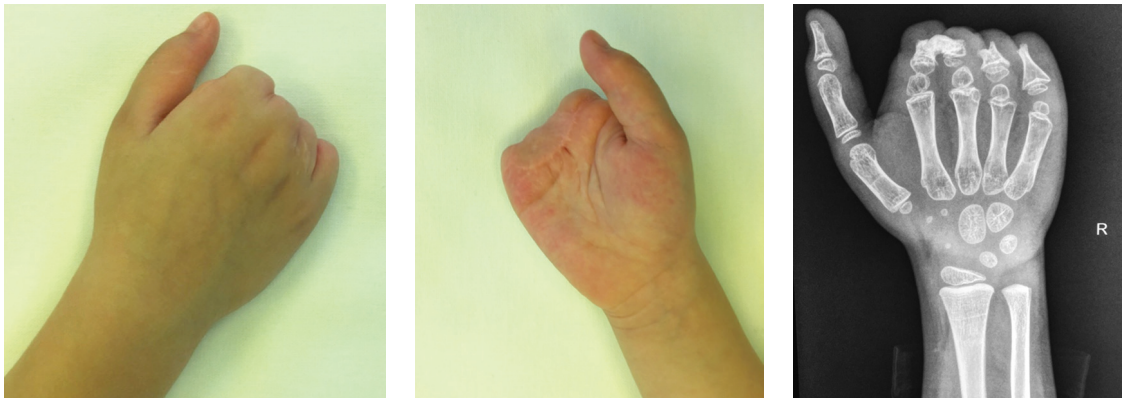
RESULTS

After conducting a complex examination of children at different intervals following multistage surgical treatment, 66% of the cases showed good or excellent results, whereas 34% showed satisfactory results.

As clinical examples, two cases of children with trauma sequelae are presented. One patient underwent one-stage reconstruction of fingers 2–5, and the other underwent reconstruction of fingers 1–4 of the hand.

Case 1

At the age of 2.5 years, a girl lost four fingers (2–5) on her right hand after it fell into the neck of an electric meat grinder. Primary surgical treatment and combined skin plasty were performed at her place of residence in Zaporozhye. At age 4 years, she was admitted to the Turner National Medical Research Center for Pediatric Traumatology and Orthopedics for surgical treatment of the stumps of fingers 2–5 (Fig. 1).



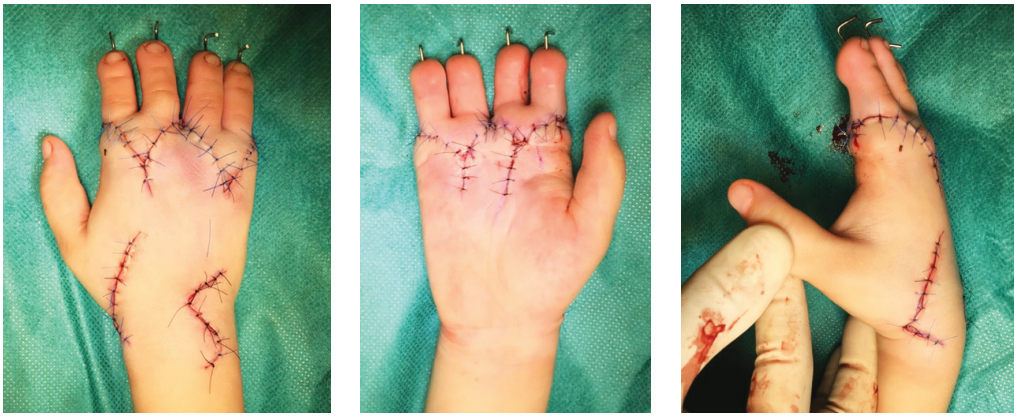
a *b* *c*

Fig. 1. Photo (*a*, *b*) and X-ray (*c*) images of the child's right hand during hospitalization at the Turner Scientific Research Institute for Children's Orthopedics (before the start of surgical treatment)

Рис. 1. Фото (*a*, *b*) и рентгенограмма (*c*) правой кисти ребенка при госпитализации в ФГБУ «НМИЦ ДТО им. Г.И. Турнера» (до начала хирургического лечения)

The initial procedure involved transplanting four toes (two from each foot) to replace fingers 2–5 on the right hand (Fig. 2). Subsequently, additional plastic surgeries were performed to enhance both the aesthetic and functional results of the finger restoration (Fig. 3).

The patient and her parents expressed complete satisfaction with the treatment outcome. Currently, the girl is fully independent (Fig. 4), excels academically, assists her mother with household tasks (Figs. 5 and 6), and participates in gymnastics (Fig. 7).



a *b* *c*

Fig. 2. Appearance immediately after transplanting the toes from both feet into the position of fingers II–V of the right hand
Рис. 2. Внешний вид руки непосредственно после пересадки пальцев с обеих стоп в позицию II–V пальцев правой кисти

Fig. 3. Photo of the hands after the completion of multistage surgical treatment
Рис. 3. Фото кистей после окончания многоэтапного хирургического лечения

a *b* *c*

Fig. 4. Functional result of the hand after the restoration of four fingers: *a* — ability to bend the restored fingers into a fist; *b*, *c* — gripping capabilities of the right hand
Рис. 4. Функциональный результат кисти после восстановления 4 пальцев: *a* — возможности сгибания восстановленных пальцев в кулак; *b*, *c* — возможности схватов правой кисти

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Fig. 5. Patient's manual skills
Рис. 5. Мануальные навыки пациентки

Fig. 6. One of the girls' hobbies is modeling figures from plasticine
Рис. 6. Одно из увлечений пациентки — лепка фигурок из пластилина

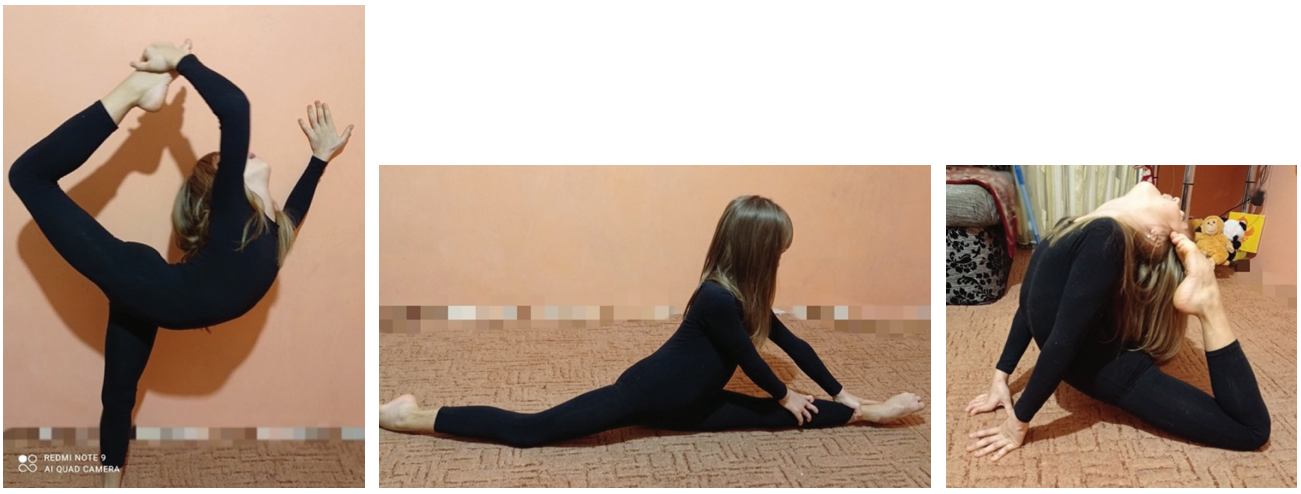


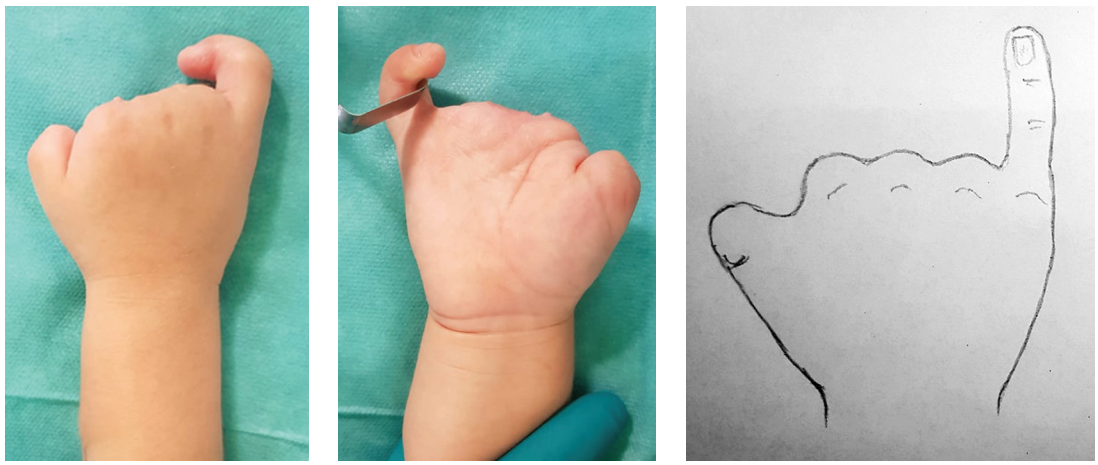
Fig. 7. Child playing sports
Рис. 7. Ребенок занимается спортом

Case 2

The second clinical case differed significantly from the first as it required the restoration of function in five fingers, including the separation of a graft from toes 2–3 of one foot to create two fingers. These were then used to reconstruct fingers 1 and 2, bridging a deep and wide gap between them. Both fingers received nourishment from a single vascular bundle, which included an artery and a vein. This method was patented under invention no. 2762616, dated December 21, 2021.

A 3-year-old boy was diagnosed with a posttraumatic deformity of the right hand. According to the patient's medical history, the child's hand got caught in an electric meat grinder. Primary surgical treatment was performed at the patient's residence. Because of the injury, only the V finger and proximal fragments of the main phalanges of fingers 1–4 were preserved. The patient's V finger was deformed and had limited function due to flexion contracture. The grip function was absent (Fig. 8). To restore hand function, microsurgical autotransplantation of two autograft blocks from the patient's toes 2–3 on both feet was performed to reconstruct fingers 1–4.

To separate toes 2–3 of the monoblock, an incision was made in the interfinger gap with a continuation along the dorsal and palm surfaces of the graft (Figs. 9 and 10). The arterial fork on the plantar surface at the base of toes 2–3 was isolated, and a branch of the plantar innominate artery of toe 2 was ligated (Fig. 11, *c, d*, *7, 8*). The common plantar nerve is longitudinally divided. On the dorsal surface, small venous branches were coagulated (Figs. 11, *g, 11*). The main



a *b* *c*

Fig. 8. Condition of the right hand of a 3-year-old child with a complication of injury: *a* — view of the hand from the dorsal surface; *b* — view from the palmar surface; *c* — schematic of the hand before surgery
Рис. 8. Состояние правой кисти ребенка 3 лет с последствием травмы: *a* — вид кисти с тыльной поверхности; *b* — вид с ладонной поверхности; *c* — схема кисти до операции

a *b*

Fig. 9. Marking of incisions on the hand during surgical treatment: *a* — view of the marking from the dorsal surface; *b* — view from the palmar surface
Рис. 9. Разметка разрезов на кисти во время оперативного лечения: *a* — вид разметки с тыльной поверхности; *b* — вид с ладонной поверхности

a *b* *c*

Fig. 10. Stages of mobilization of toe II–III block autograft of the left foot with simultaneous separation of toes II and III on a common vascular pedicle: *a* — appearance of the feet before surgery; *b* — isolated (vascular) pedicle of toe II–III block autograft; *c* — toes II and III of the left foot after their separation

Рис. 10. Этапы выделения аутотрансплантата-блока II–III пальцев левой стопы с одномоментным разделением II и III пальцев на общей сосудистой ножке: *a* — внешний вид стоп перед операцией; *b* — выделенная (сосудистая) ножка аутотрансплантата-блока II–III пальцев стопы; *c* — II и III пальцы левой стопы после их разделения

venous trunks from toes 2 and 3 to the common venous pedicle, the great saphenous vein, were preserved. The toes of the single-second autograft block are disconnected while preserving blood supply from a common vascular pedicle, which consists of the dorsal artery of the foot (Fig. 11, *c, 1*) and the great saphenous vein (Fig. 11, *f, 9*).

Incisions were made along the end surface of the right hand in the area of the preserved fragments of the main phalanges of fingers 1–4. The incisions were then continued to the dorsal and palm surfaces of the hand. The extensor tendons of fingers 1–4 and venous branches of the *v. basilica* were identified on the dorsal surface of the hand. On the palmar surface of the hand, the tendons of finger flexors 2–5 and the common finger nerves were isolated. The radial artery and *v. cephalica* were isolated from the incision in the anatomical snuffbox. The preserved fragments of the main phalanges of fingers 1–4 were exposed and resected.

The toes of the feet were used as autografts and transplanted to the hand in the finger 1–4 position. The grafts were fixed with spokes along the axis. The donor finger 2 of the first block was placed in the finger 3 position of the hand, and the donor finger 3 of the first block was placed in the finger 4 position of the hand. The donor finger 2 of the disconnected second block was placed in the finger 2 position of the hand, and the donor finger 3 of the second block was placed in the finger 1 position of the hand. The flexor and extensor tendons and donor and recipient toe nerves were sutured. End-to-end anastomoses were performed between the dorsal foot artery of the autograft from the left foot and the proximal end of the dissected radial artery (Fig. 12, *e, 12*). The arterial pedicle of the second autograft from the right foot was anastomosed with the distal fragment of the radial artery (Fig. 12, *e, 13*), which is a continuation of the deep palmar arterial arch. Anastomoses were made between the veins of the grafts and the recipient area. Stable blood flow was restored in the autografts after the clips were removed within 15–20 s. The wounds were then sutured layer by layer (Fig. 12 *a–c*). Finally, an aseptic dressing was applied and plaster splints were placed on the upper and lower extremities. The postoperative period was without complications. Anticoagulant therapy was administered, and the sutures were removed on postoperative day 14. X-ray radiography was performed 5 weeks later, which confirmed sufficient consolidation of bone fragments, and the fixation spokes were removed.

This method enables the one-stage reconstruction of four fingers. This involves separating a block of toes 2–3 from the feet and placing a toe in the position of finger 1. This finger is separated from the rest by a deep interfinger gap and is positioned in opposition to the other (long) fingers of the hand.

Foot biomechanical studies revealed no significant changes in foot function during the initial 6 months following surgery. However, eventually, the foot function fully recovered (Fig. 13).

Analysis of stabilometric data following toe transplantation from the feet revealed no statistically significant displacement of the patient's center of pressure in either the frontal or sagittal plane, indicating that the patient's balance remained stable. After surgery, the eccentricity of the ellipse decreased significantly. This suggests that the zone of oscillations of the center of pressure approached the shape of a circle because of an increase in oscillations in the frontal plane (Fig. 14).

When borrowing toes from donor feet, the cosmetic aspects of changes in the operated foot become prominent. The best plantographic characteristics were obtained when

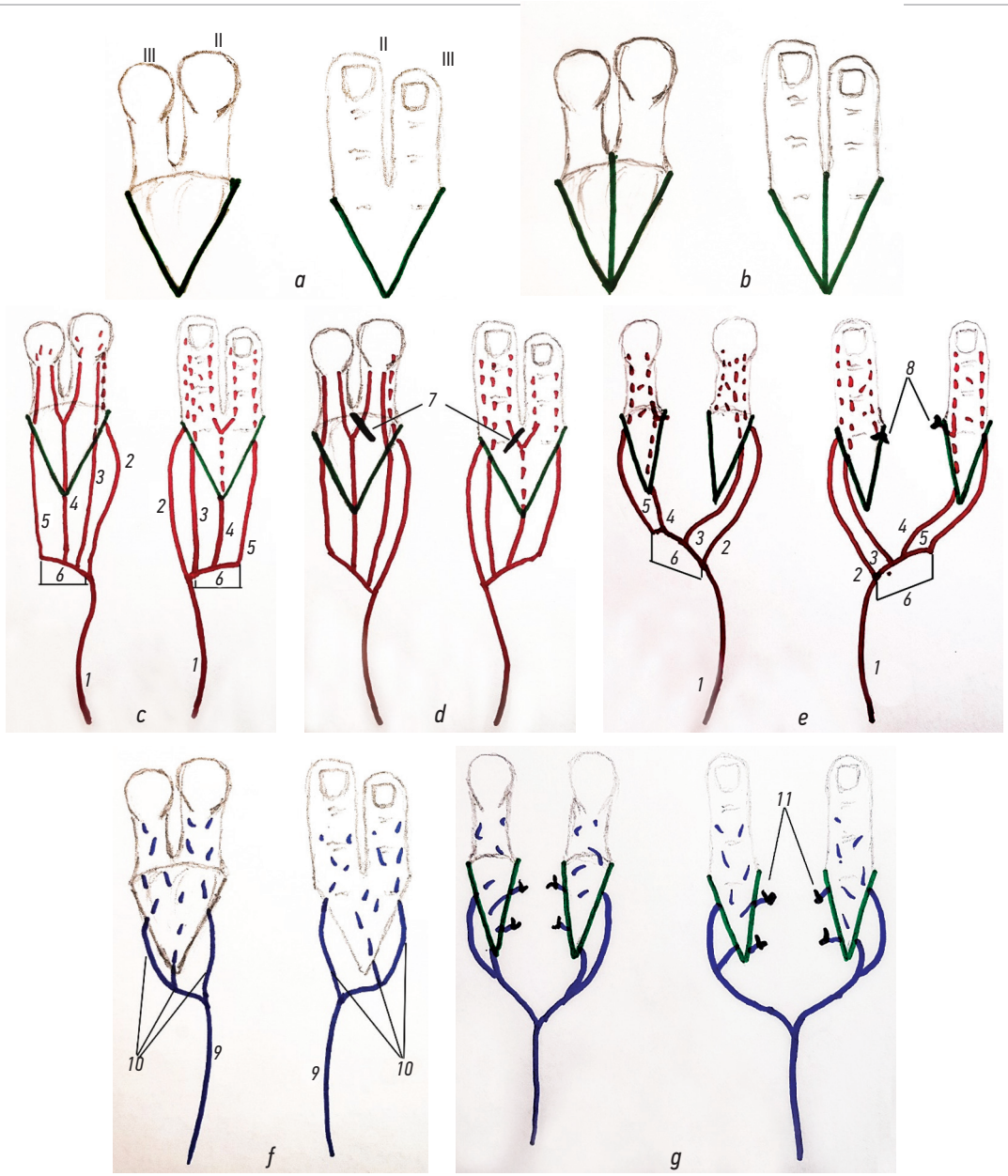


Fig. 11. Schemes of the step-by-step separation of toes II and III of the left foot into two autografts with a common vascular pedicle: *a* — scheme of the incisions on the foot; *b* — scheme of the incisions between toes II–III of the autograft block; *c,* scheme of the arterial source of autograft block (*1* — dorsal artery of the foot; *2* — dorsal metatarsal artery; *3* — first plantar metatarsal artery; *4,* second plantar metatarsal artery; *5* — third plantar metatarsal artery; *6* — fragment of the plantar arterial arch); *d* — scheme of the stage of the second plantar metatarsal artery branch intersection, namely, digital artery of finger II (*7* — place of intersection); *e* — scheme of the separation of the autograft-block's toes (*1* — dorsal artery of the foot; *2* — dorsal metatarsal artery; *3* — first plantar metatarsal artery; *4,* second plantar metatarsal artery; *5* — third plantar metatarsal artery; *6* — fragment plantar arterial arch; *8* — site of ligation (coagulation) of the digital artery of toe II); *f* — scheme of the venous source of the autograft block of toes II–III (*9* — great saphenous vein of the foot; *10* — branches of the great saphenous vein to the toes of the autograft block); *g* — scheme of the separation of the autograft block's veins (*11* — site of ligation of the venous branches between toes II–III)

Рис. 11. Схемы поэтапного разделения II и III пальцев левой стопы на два аутотрансплантата на общей сосудистой ножке: *a* — схема разрезов на стопе; *b* — схема разрезов между II–III пальцами аутотрансплантата-блока; *c* — схема артериального русла аутотрансплантата-блока II–III пальцев стопы (*1* — тыльная артерия стопы, *2* — тыльная плюсневая артерия, *3* — первая подошвенная плюсневая артерия, *4* — вторая подошвенная плюсневая артерия, *5* — третья подошвенная плюсневая артерия, *6* — фрагмент подошвенной артериальной дуги); *d* — схема этапа пересечения ветви второй подошвенной плюсневой артерии, а именно собственной пальцевой артерии II пальца (*7* — место пересечения); *e* — схема разделения пальцев аутотрансплантата-блока (*1* — тыльная артерия стопы, *2* — тыльная плюсневая артерия, *3* — первая подошвенная плюсневая артерия, *4* — вторая подошвенная плюсневая артерия, *5* — третья подошвенная плюсневая артерия, *6* — фрагмент подошвенной артериальной дуги, *8* — место перевязки (коагуляции) собственной пальцевой артерии II пальца; *f* — схема венозного русла аутотрансплантата-блока II–III пальцев стопы (*9* — большая подкожная вена стопы, *10* — ветви большой подкожной вены стопы к пальцам аутотрансплантата-блока); *g* — схема разделения вен аутотрансплантата-блока II-III пальцев стопы (*11* — место перевязки венозных ветвей между II–III пальцами)

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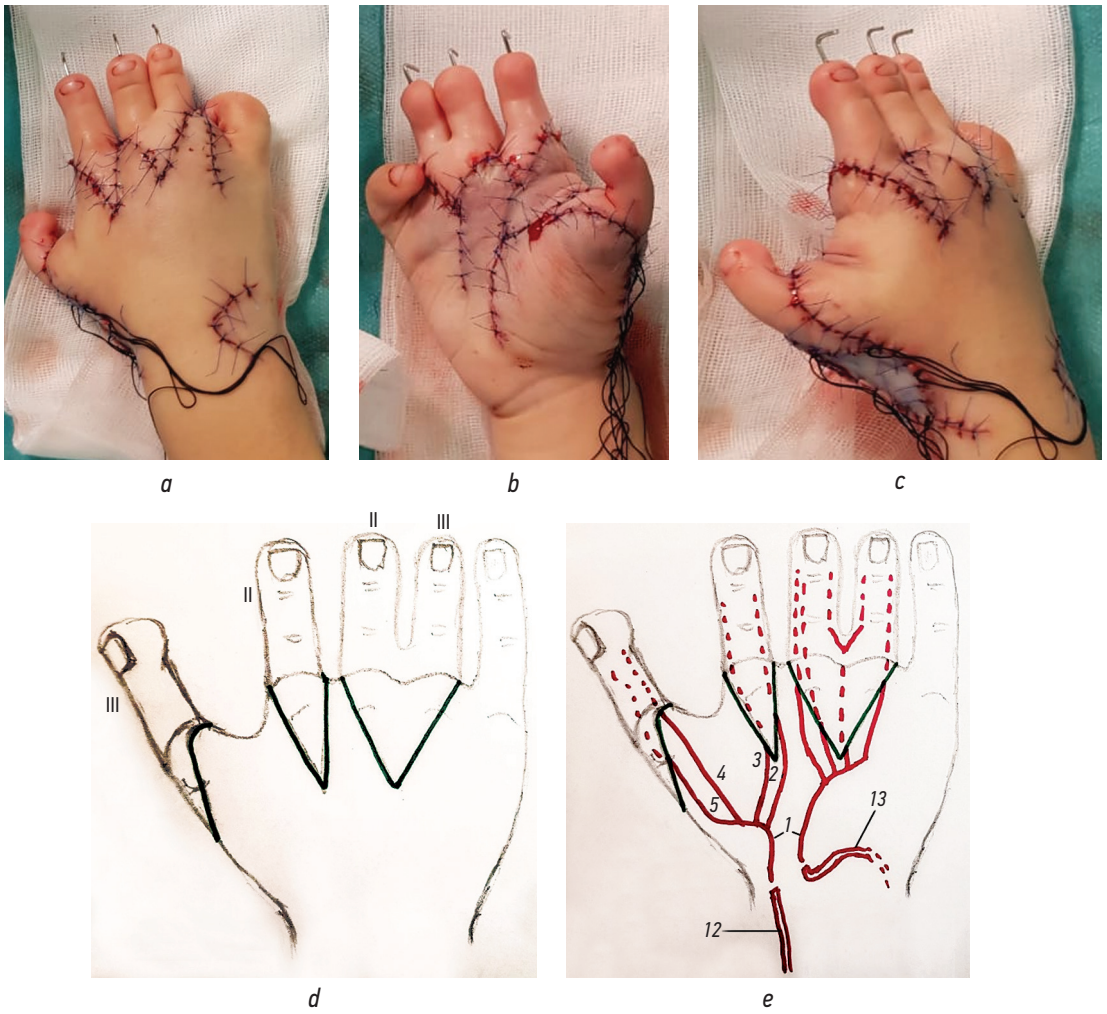

Fig. 12. Appearance of the hand immediately after the restoration of fingers I–IV of the right hand in a 3-year-old child, with complications of injury, using autotransplantation of two finger II–III autograft blocks of both feet with simultaneous separation of the toes in one autograft: *a* — view from the hand dorsum; *b* — view from palmar surface of the hand; *c* — view from the radial surface of the hand; *d,* scheme of the autograft location on the hand; *e* — scheme of the location and anastomosis of the autograft's arteries (*1* — dorsal foot artery; *2* — dorsal metatarsal artery; *3* — first plantar metatarsal artery; *4* — second plantar metatarsal artery; *5* — third plantar metatarsal artery; *6* — fragment of the plantar arterial arch; *12* — proximal fragment of the dissected radial artery; *13* — distal fragment of the dissected radial artery)

Рис. 12. Внешний вид кисти непосредственно после восстановления I–IV пальцев правой кисти у ребенка 3 лет с последствием травмы методом аутотрансплантации двух аутотрансплантатов-блоков II–III пальцев обеих стоп с одномоментным разделением пальцев одного аутотрансплантата: *a* — вид с тыльной поверхности кисти; *b* — вид с ладонной поверхности кисти; *c* — вид с лучевой поверхности кисти; *d* — схема расположения аутотрансплантатов пальцев на кисти; *e* — схема расположения и анастомозирования артерий аутотрансплантатов пальцев стоп (*1* — тыльная артерия стопы, *2* — тыльная плюсневая артерия, *3* — первая подошвенная плюсневая артерия, *4* — вторая подошвенная плюсневая артерия, *5* — третья подошвенная плюсневая артерия, *6* — фрагмент подошвенной артериальной дуги, *12* — проксимальный фрагмент рассеченной лучевой артерии, *13* — дистальный фрагмент рассеченной лучевой артерии)

the same number of toes were borrowed bilaterally from each foot, as shown by the comparison of parameters in patients with symmetrical and asymmetrical toe borrowing. The computerized stabilometry method did not detect any significant instability in the patient's stance after surgical interventions involving the transplantation of toes from donor feet. This can be attributed to the activation of compensatory mechanisms that maintain support and body balance, thereby mitigating the physical damage caused by surgical intervention.

DISCUSSION

The concept of transplanting toes to replace fingers was first introduced in the late nineteenth century. The procedure was initially performed in two stages, in a nonfree version. In 1898, Nicoladoni transplanted toe 2 to finger 1 of a 5-year-old boy using a temporary feeding pedicle. During the initial stage, the surgeons sutured toe 2 to the stump of finger 1 while preserving the plantar feeding pedicle and suturing the flexor and extensor tendons. A month later, during the second stage, the pedicle was severed. Unfortunately,

partial necrosis of the nail phalanx developed. After a second surgery similar to the first in 1900, complete engraftment occurred. Several surgeons, including those in Russia, have used this surgical treatment method for some time. In 1911, Dr. Klemm successfully performed this intervention on an adult patient. Different modifications of this method were developed, and the timing of stem cutting ranged from 2 to 6 weeks (Belousov, [11]).

However, this method of finger reconstruction has several significant disadvantages. First, the forced position in which the toe of the foot is sewn to the hand becomes unbearable for the patient over time. Second, the operation does not restore nerve function, resulting in a lack of stereognostic sensitivity. Third, the blood supply to the finger is poor, leading to unsatisfactory tendon function. Finally, trophic disorders often develop in the graft, and in children, the finger grows slower than the hand (Davis J.E., 1964; cited by A.E. Belousov [11]). Therefore, this surgery was not widely used because the functional result did not justify the patient's suffering.

The use of optical magnification in the operating room has opened new perspectives and opportunities for the development of surgery. Since the second half of the twentieth century, microvascular surgery has been actively developing.

The initial single-stage finger transplantation was performed by Buncke in 1964, in an experiment on monkeys [12]. Furthermore, Yang reported a successful microsurgical transplantation of toe 2 in 1966, and in 1968, Cobett performed a successful transplantation of toe 1. Since then, this technique has been widely used in adults for hand reconstruction after trauma.

In 1977, O'Brien [13] published the results of the first foot-to-hand finger transplantation in a child with a congenital

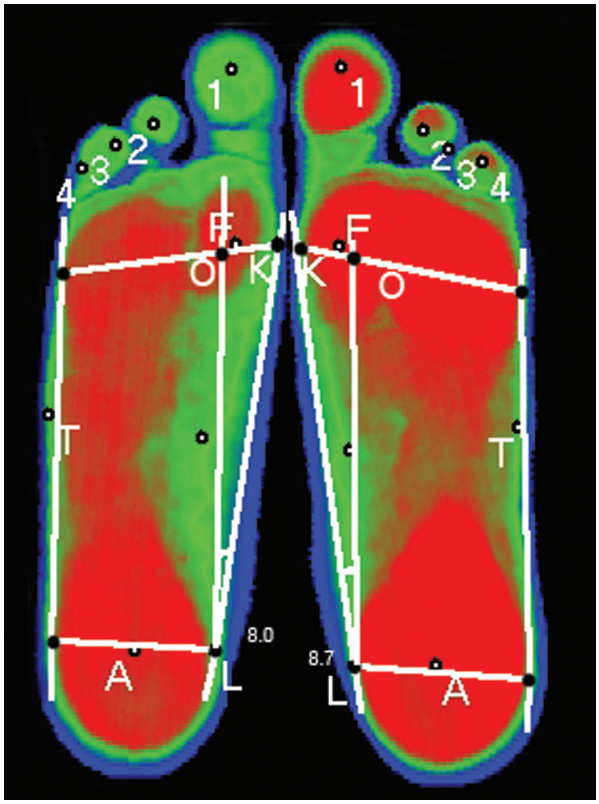

Fig. 13. Plantogram of the feet of a 4-year-old patient: 1 year after the operation of bilateral taking of toe II–III block. (Despite noticeable changes in the imprint's anatomical shape of the operated feet, no difference was found in the width of their anterior parts. Foot function was not impaired, and the load distribution on both feet was even)
Рис. 13. Плантограмма стоп пациентки 4 лет: через 1 год после операции двустороннего заимствования блока II–III пальцев стоп. (Несмотря на заметные изменения анатомической формы отпечатка оперированных стоп, отсутствует разница в ширине их передних отделов. Опорная функция стоп не нарушена, распределение нагрузки на обе стопы равномерное)

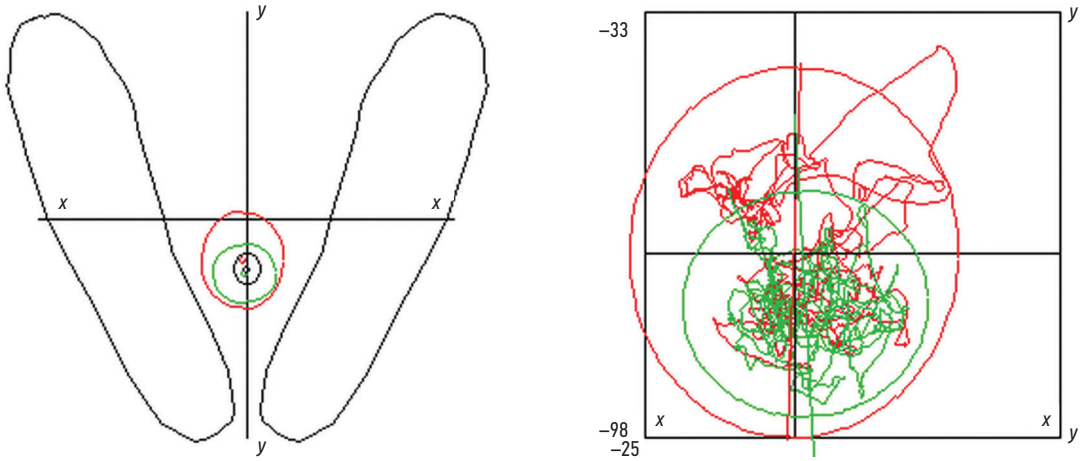

Fig. 14. Computer statokinesiogram of the patient after toe-to-hand transfer from the right foot. Reducing the eccentricity of the center-of-pressure (CoP) deviation from an ellipse with open eyes to a circle with closed eyes. Left: projection of the child's real CoP relative to the average normative position of the CoP; right, graphical representation of the real statokinessiogram
Рис. 14. Компьютерная статокинезиограмма пациента после операции заимствования пальца с правой стопы. Снижение эксцентриситета девиации центра давления (ЦД) от эллипса при открытых глазах до окружности — при закрытых. Слева: проекция реального ЦД ребенка относительно среднего нормативного положения ЦД; справа: графическое изображение реальной статокинезиограммы

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hand anomaly. Subsequently, several publications on the use of this method in children appeared in foreign press [4, 10, 14].

In pediatric practice, toe 2 of a foot, toes 2 of both feet, or block of toes 2–3 from one or both feet are most often used as a transplant [2]. This surgery offers several advantages, including the restoration of sufficient function (mobile joints and good sensitivity), preservation of the ability to grow, and a good aesthetic result (the presence of a nail plate with thickness and size similar to a healthy toe). However, the potential drawbacks of this procedure should be mentioned, including technical difficulties during surgery, potential damage to the foot, and a lengthy rehabilitation period required to achieve an acceptable functional outcome [15–17].

Several variations of this procedure have been performed, including multiple toe transplants in a single surgical procedure. A group of Spanish hand surgeons analyzed 10 cases of single-stage multiple toe transplants for the reconstruction of adult hand fingers [18]. Surgeons are known to include up to three toes in a single foot graft. In nine cases, toes 1–2 were used, and in one case, toes 1–3 were used. The maximum number of toes transplanted from both feet in a single publication was six, with three toes from each foot used to reconstruct fingers 1–3 on both hands of an adult patient who lost all fingers because of trauma. However, the surgical treatment consisted of multiple stages, with two autografts performed on each hand [19]. Additionally, reconstructive treatment for the "metacarpal hand" (absence of all fingers of the hand, only the metacarpal bones are preserved) is challenging. Several studies have used microsurgical autotransplantation of the toes to restore hand function [20–22].

Reports on multiple-toe-to-hand transplants in children are few [1, 2]. No reports on one-stage transplantation of four toes to one hand were found in the available literature.

The decision to perform a one-stage transplantation of four toes is significant to the surgeon, who must carefully consider all the advantages and disadvantages of the procedure. This study identified the primary criteria, indications, and contraindications for microsurgical autotransplantation of the four toes from both feet to the hand:

- The presence of rough posttraumatic scars; signs of damage to crucial anatomical structures including the vessels, nerves, and tendons; and signs of widespread damage to the soft tissues of the hand and forearm;
- The safety and function of the metacarpophalangeal joints and the level of finger detachment owing to congenital underdevelopment were assessed;
- Functional capabilities of the damaged or underdeveloped hand and the presence of bilateral grip;
- Motivation and attitude of parents toward long-term multistage surgical and conservative treatment, which is the key to success and obtaining the maximum aesthetic and functional result.

CONCLUSIONS

This study demonstrated that microsurgical autografting of the toes from the foot to the hand is an effective treatment for congenital and acquired hand deformities in children. The autografts retain their viability because of blood circulation restoration in the transplanted toes, which subsequently ensures stable growth and development of the hand and restoration of motor and sensory function. In cases of congenital underdevelopment or posttraumatic absence of several fingers, one-stage multiple toe transplantation from the feet is possible. Our experience with restoring four fingers by transplanting two toes from each foot in children has shown its relevance and effectiveness. The reconstructive treatment enabled the patients to use their hands in daily life, participate in their favorite activities, and adapt socially. Microsurgical finger reconstruction remains the preferred treatment method along with other surgical methods and prosthetic fingers in children.

ADDITIONAL INFORMATION

Author's contribution. Thereby, author made a substantial contribution to the conception of the study, acquisition, analysis, interpretation of data for the work, drafting and revising the article, final approval of the version to be published and agree to be accountable for all aspects of the study.

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Competing interests. The author declare that they have no competing interests.

Consent for publication. Written consent was obtained from the patients for publication of relevant medical information and all of accompanying images within the manuscript.

ДОПОЛНИТЕЛЬНАЯ ИНФОРМАЦИЯ

Вклад автора. Автор внес существенный вклад в разработку концепции, проведение исследования и подготовку статьи, прочел и одобрил финальную версию перед публикацией.

Источник финансирования. Автор заявляет об отсутствии внешнего финансирования при проведении исследования и подготовки публикации.

Конфликт интересов. Автор декларирует отсутствие явных и потенциальных конфликтов интересов, связанных с проведенным исследованием и публикацией настоящей статьи.

Информированное согласие на публикацию. Автор получил письменное согласие законных представителей пациентов на публикацию медицинских данных и фотографий.

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