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Present technique and long-term results of toe-to-antebrachial stump transplantation

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Summary Complete hand amputation has been considered conventionally as an indication for the use of mechanical prosthetic devices in order to regain some hand like function.

A microsurgical option to create a new pinching ability after wrist amputation has been used in a series of 13 patients. The actual operation technique is presented in detail. It was designed by the senior author in 1981 and applied into clinical use in 1983. In order to evaluate the functional results and patient satisfaction in long-term, a questionnaire was sent to 12 patients and 11 patients were interviewed, examined clinically and studied with a hand function scoring test according Sollerman. The operated series consist of 12 adults with posttraumatic distal antebrachial or wrist amputations and 1 adolescent boy with a congenital wrist level amputation. There were 3 females and 10 males in the series. The satisfaction to achieved result was generally good.

The ADL section of Tamai score and the one we used correlated well with each other and patient satisfaction. Sollerman hand function test gave worse results in two blind patients and same occurred in two short antebrachial stump patients. However the satisfaction was much better in Tamai score among blind patients, with wrist amputation level amputations. In our opinion this single toe transfer method gives an acceptable pinch reconstruction for hand amputation patients. We measured pinch strength and total active motion. They averaged about half of the normal values. The reconstruction is suitable to the patients, who are not willing to donate multiple toes or who are aware and concerned about the risks of human hand transplantation, which necessarily will need a life-long immunosuppressive medication to prevent from rejection.

Possibilities for the reconstruction of posttraumatic wrist or distal forearm amputation stump are very limited. There is a complete loss of important functional elements of the hand; there are no fingers or mobile joints, sensible glabrous skin is usually lost completely, the wrist joint is either completely absent or just part of the proximal row may still

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exist. Depending of the injury level the distal radio-ulnar joint is also absent. The skin cover may be of poor quality and less resistant to daily use. There is, however, a hidden potential at the antebrachial stump for toe-to-antebrachial-stump reconstruction (toe to AB-stump) because of the presence of multiple functional tendon-muscle units inside the forearm. Although some attempts at allogenic human hand transplantation have taken place during the last seven years, an autogenous microsurgical pinch reconstruction with a single or multiple toe-transplantations is still considered a realistic and safe chance for the victims of traumatic hand amputation in order to regain a partial useful hand function.[1,2]

Before the microsurgical era the Krukenberg procedure was used for the rehabilitation of the victims of bilateral hand loss when the antebrachial stumps were long enough to form a pinching forceps.[3] A different reconstruction with toe transfer was also possible using Nicoladoni type procedure. Professor Oehlecker performed a distal forearm stump plasty with a great-toe-transfer in 1919.[4] Later on microsurgical methods allowed a direct free tissue transfer and the Krukenberg procedure has become less popular. In the 1970's the Chinese microsurgeons developed microsurgical hand reconstruction models for wrist amputees.[5] They used either two second-toe transfers at the tip of the radius stump or they used a metallic implant which aided in positioning the multiple toes at wrist level amputations. Furnas and Achauer published in 1983 a simple method where a great-toe was used on the side of the radius to form a pinch grip.[6] A more sophisticated technique to create a grip at wrist amputation level was then proposed by Vilkki using a three jointed second toe with a hemipulp flap from great toe after osteoplastic modelling of the distal radius.[7] The experience gained from 13 cases using this last mentioned method with its modifications is the basis for this article.

General operative principles in this series

The prerequisites at wrist or distal forearm for successful reconstruction are dependent on stump length, the relationship between remaining lengths of radius and ulna, availability of adequate skin coverage, distance to sensory nerve stumps and adequate tendons or muscles to motorize the transferred toe. The described neo-thumb reconstruction (Fig. 1) by shifting the transferred toe more proximally in the stump makes the procedure easier and it will improve the quality of neural and vascular connections. Also possible posttraumatic severe scar in the distal antebrachial stump area is not so disturbing when the neo-pollex is placed more proximally. This position will allow the distal stump to act as a stable post but the actual length of the stump will not increase in this reconstruction. In wrist amputation cases an osteoplastic modelling of the distal radius is useful. When available, the DRU-joint function is always preserved. Resection of the radial half of the broad radius will help in creating the larger web area. It also will make the plateau of the opposing post wider and makes the alignment of the transplanted toe more convenient in order to reach to the opposing post during flexion effort. The skin coverage becomes easier due to bone resection.

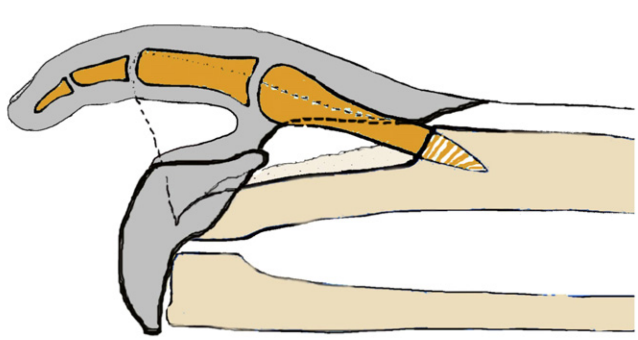

Figure 1 The positioning of the transplanted toe and the hemipulp flap (coloured in grey).

A single toe with three movable joints will need at least 5 functional motor units to work properly. Two extensors, two flexors and the three intrinsics should be brought into balance in order to create the necessary power and mobility to stabilize and move the toe. In an intact forearm there are over 20 long tendon-muscle units and the selection of tendons to be transferred is usually easy in fresh cases. When many months have elapsed after amputation the finger extensors and flexors inside the forearm may be less suitable because of long inactivity time and secondary atrophy and contractures of the muscles. The commonest motors used have been ECRL, ECRB, APL, BR, PL, FPL, and FDS II - IV muscles. Both intrinsic tendons of the toe should be reconstructed for proper balance and sideway movements and functional stability of the MTP-joint during extension. The reconstruction of lumbrical tendon is also beneficial. For extensor function a full intrinsic activation is a prerequisite and in addition to that two strong extensor muscles are needed to activate the toe extensors properly. For adequate thumb flexion at least one strong muscle is needed. The second toe includes long and short flexors and when the PIP-joint mobility is the aim in mimicking normal thumb flexion the activation of the short flexor is most important. When the long flexor is also connected to the same motor then the stability of the toe tip remains good when the short flexor will be activated but the tip is not flexing too much.

The best donor nerves are the median nerve and the radial nerve at distal antebrachial stump. The idea to position a toe transplant seven or eight centimetres proximally from the stump tip will limit the need for grafts thus enhancing for better sensory recovery and easier microsurgical anastomoses of the nutrient vessels. In cases with long delay after trauma the graft revascularization may still require the use of vein grafts and harvesting a more proximal donor artery may become necessary. The same may apply to the vein system reconstruction especially when forearm skin has become avulsed during the original trauma.

The ipsilateral second toe is used for creation of a 'neo-thumb'. When the post side is covered with poor quality skin or badly scarred tissue after trauma, a glabrous hemipulp flap or a partial wrap-around-type flap from the great toe is prepared together with a long three jointed second-toe transplant (Fig. 2a and b). This glabrous skin flap from great toe will be used to cover the post area and it creates a 'mini-palm with prehension'. In some wrist amputation stumps there may be enough volar sensory glabrous skin and in these cases this island flap extension of the graft may be

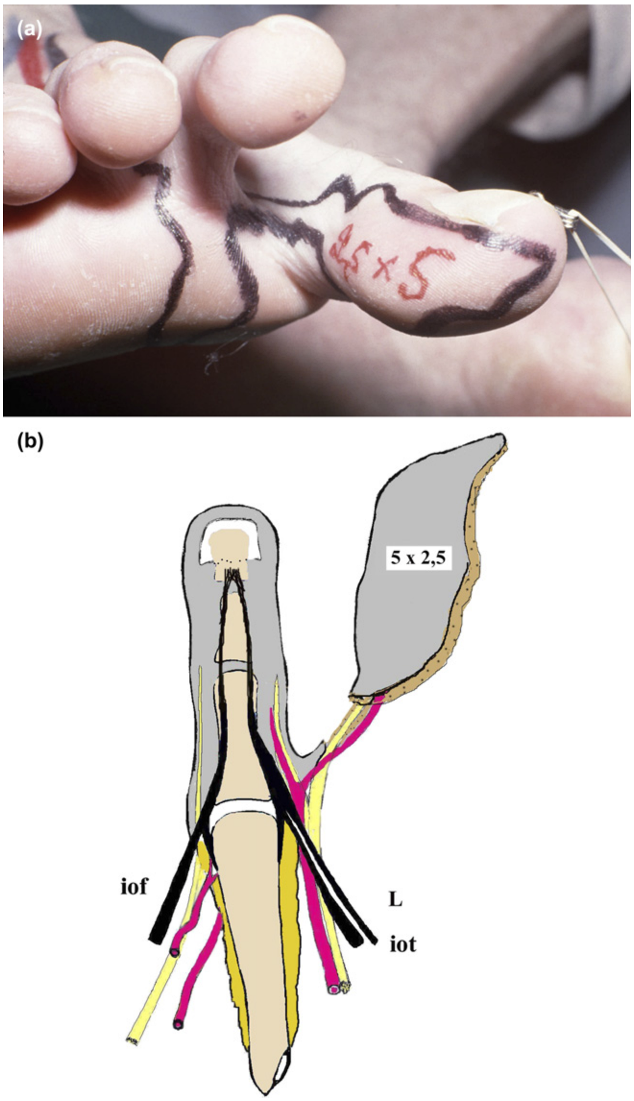

Figure 2 a and b. The toe transplant and the hemipulp flap are shown clinically (2a) and schematically (2b). Intrinsic tendons: iof = fibular interosseus tendon, iot = tibial interosseus tendon and L = lumbrical tendon.

unnecessary. The nerves (fibular plantar digital nerve of hallux) to the hemipulp flap with all four second toe nerves are most essential for the later function.

The appearance and function of the foot is not disturbed when the primary closure at the foot first web space is achieved. A skin graft is used only for the secondary defect at the fibular side of great toe.

Indications and timing

An adult patient with uni- or bilateral hand amputation at wrist level or within distal 10 cm of the antebrachium can benefit from this method. The loss of vision, induced by explosion injuries, is sometimes present and these patients can not be rehabilitated with prosthetic hands. In the literature there are similar reconstruction attempts for patients with explosion, severe crush and frostbite injuries.[8–11]

In small children similar reconstruction is not feasible when the radius and ulna have intact and well growing growth plates distally. The toe transfers should be done distally to the physeal plate and that requires different techniques.[12] However, later on in adolescence, when the longitudinal growth is almost finished this operation can be a useful option.

The earlier after trauma the reconstruction can be accomplished, the better the result.

The motor units are still quite normal in amplitude and their tension is easy to adjust. After an early reconstruction within the first 2 months after a trauma, the patient can easily learn to use the new thumb when the muscles have partly their original capacity and control.

In a special situations a similar emergency operation can be accomplished using a single finger if all other hand structures have become lost and just a single intact finger unit happens to be available.

In older cases the muscles at antebrachial stump will need preoperative rehabilitation. Already after two or three months all tendons and muscles will be retracted and scarring has taken place between different tissues. If more time has elapsed the control of the antebrachial muscles has been forgotten and muscles have become atrophic and their power has diminished. In these cases active preoperative rehabilitation period of about one month is considered necessary. This means that those antebrachial muscles, which are selected to be used as motors for neo-thumb activation, should be well working and the patient must be clearly conscious about the function of the different muscles at his or her forearm stump. We teach the patient preoperatively to activate specifically flexor pollicis longus, extensor carpi radialis group, abductor pollicis longus, wrist flexors and other flexor and extensor groups. The training must be intensive especially during the three last weeks before operation. Longer period is necessary when a lot of time after amputation injury has elapsed and the muscles have been inactive. This re-education to use selected antebrachial muscles is beneficial for the easier postoperative rehabilitation with early controlled active motion.

Preoperative investigations and planning

The operative plan is based on the presence and location of most important structures at the stump. A Doppler ultrasound device is used for the location of functioning arteries and veins, which are marked preoperatively. The recipient nerve stumps are located by Tinel's sign (Fig. 3). Plain X-ray images of the AB-stump and the feet with clinical measurements are necessary in planning the location of the neo-thumb. A reconstruction model is designed on paper or silastic foam model to see how to position the toe transplant during the operation. Using the reconstruction model in the discussion with the patient is important and the patient should give the guidelines for the best positioning of the 'neo-thumb' according to his special needs. After the original injury the antebrachial musculature can be defective, and after avulsion injury the selection of muscles is dependant on the remaining muscular anatomy. The defect after severe avulsion injury is common in thumb and finger

Figure 3 The arteries and nerves are located preoperatively.

flexors and extensors. The availability of remaining muscles must be checked carefully and the plan for activation of the neo-thumb is done accordingly.

The ipsilateral second toe is usually used. The arterial supply to the graft area can be evaluated using ultra sound Doppler and no invasive methods for preoperative vascular evaluation have been used. The length, joint condition (MT and PIP) and mobility of the second toe as well as a need for glabrous mini palm island to cover the post area are evaluated and measured.

Actual reconstructive technique

Stump preparation

The present operative technique follows the guidelines which have been presented by the senior author.[7,13–15]

Meticulous preoperative planning will dictate the approach and incisions for antebrachial stump preparation (Fig. 4). A large longitudinal incision is placed on the distal radial aspect of the forearm and large flaps with skin and subcutaneous tissue are created both on the volar and dorsal side to expose different functional structures. Volar glabrous palmar skin with normal sensibility is meticulously preserved and used to resurface the opposing post side when possible.

Figure 4 It is important to plan preoperatively the extent of bone resection and the available muscles to be used.

Superficial radial sensory nerve, cephalic vein and radial artery are identified.

The tendons of APL, FCR and BR are identified and mobilized when needed for better amplitude. Radial wrist extensors (ECRL and ECRB) are usually available and 3–5 cm amplitude is achieved after proper mobilization. Due to the original trauma the condition of thumb and finger tendons and muscles will vary. After sharp amputation the FPL and finger flexors are readily available. Also good thumb and finger extensor tendons are available when the reconstruction is carried out within first 2–3 months after injury. After severe avulsion injury the presence of last mentioned tendon groups is less likely. Then alternative motors must be used.

The median nerve with distal neuroma is identified. In severe avulsion injuries this nerve may have become torn at a more proximal level and is not usable. Then dorsal sensory branches of the radial and ulnar nerves are usually present in the distal forearm and can be used as sensory donor nerves.

The bone resection is done opening the periosteum on the radial side in midline and resecting the radial half of distal radius up to 7 or 8 cm from the styloid thus leaving a wide plateau on the ulnar side cortex. DRU-joint is left intact when possible (Fig. 5). After bone resection the periosteum is closed over the resected bone surface at distal radius but an opening is left proximally for the toe metatarsal at the site of osteosynthesis.

Toe harvesting

The second toe with long metatarsal shaft is harvested preferably from the ipsilateral foot (simultaneously with stump preparation if two surgical teams are available.)

The vein system of the toe should include if possible two major veins. Also a 4–5 cm broad intervenous subcutaneous flap is created in between these veins when skin quality is less adequate at the stump radial side.[16,17] This veno-subcutaneous flap is very useful if the quality of distal antebrachial skin cover is poor or defective. It can be used to cover the osteosynthesis site or other important structural connections. Split skin grafts can be used over this vascularized flap when necessary. When a sensory glabrous skin is needed to cover the post side a 2.5 cm by 5 cm hemipulp flap or a larger wrap-around flap from great toe is prepared based on the toe vessels (Fig. 2a and b). This is especially important if the original stump skin is scarred and poor in quality or sensory function. This flap is based on the first DMTA and concomitant veins as well as fibular plantar nerve of the great toe.

First DMTA and second DMTA as well as II/III PMTA are taken with the graft. Dorsal arteries can be left connected to the dorsalis pedis artery and a longer pedicle is taken when necessary. The plantar artery system is taken with a short pedicle until it unites with the plantar arch and is marked. All four toe nerves are dissected with the lengths necessary to join with antebrachial sensory donor nerves. The extrinsic tendons are dissected in suitable lengths.

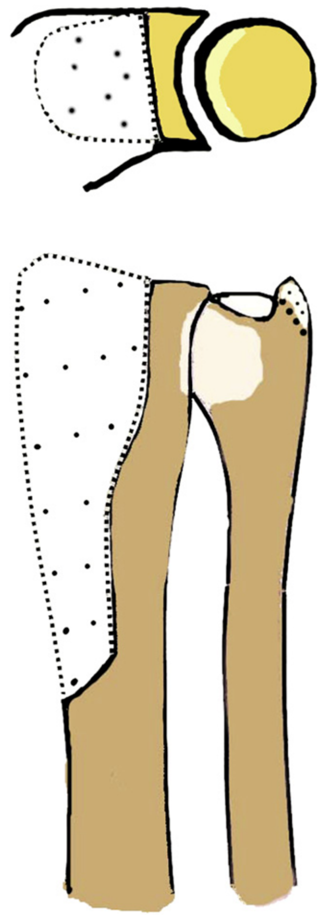

Figure 5 Bone resection shown schematically in longitudinal and transverse plains.

Special care must be taken not to open the flexor tendon sheet at metatarsophalangeal joint level. This is important in order to prevent from adhesions and to provide good gliding of the tendons close to the bone resection area and the osteosynthesis site. The intrinsics are also dissected with the toe. Lumbrical tendon on tibial side is taken with a piece of muscle and the best parts of interosseous tendons are identified and marked inside the muscles. The interosseous muscle tissue is resected leaving only a thin layer on each side of the metatarsal bone so that the bone circulation is not in danger. The length of the metatarsal bone needed to the graft is usually about 5—6 cm and the plantar lip of the proximal bone end is left longer in order to fit into radius during reconstruction.

Neo-thumb reconstruction

After osteoplastic resection there is a hole in the radius at the distance of 7 or 8 cm from the tip in order to accommodate the graft. The proximal end of metatarsal bone should be carved to fit inside the radius for additional stability. The alignment and proper length of the metatarsal bone is important. It should be almost parallel to radius or only slightly (15 degrees) abducted radial and palmar wards. This is necessary for good closing function as MTP- joint has only a limited range of flexion while the ability to hyperextend is much greater. The aim is to place MTP joint-level about 4—5 cm proximally from the stump tip. This depends on toe length and the location of aimed contact area in the new minipalm. Some space between the MTP-joint and the radius is necessary for flexor tendons to allow free gliding and attention must be paid that no uncovered bone surface is left in contact with tendons. In a young patient a large bone cortex flap with intact periosteum can be lateralized in order to achieve a wider web space. In such a case the toe is placed at the end of the elevated bone flap. There is lateral deviation ability in MTP-joint and the toe tip must be able to reach the opposing stump surface within this range. Fixation of the bone is secured with compression wiring and K-wires in best position. If there is some part of the wrist joint available the bone may be fixed into more palmar position in order to make use of the possible active flexion of the remaining wrist (Fig. 6).

Reconstruction of all seven tendons is essential for balanced function. It means also meticulous intrinsic repair (Fig. 7). First the lateral stability of toe is managed with two tendon transfers. Usually APL transfer to ulnar side interosseous tendon and one of the superficial flexors to radial side interosseous tendon gives a good balance. Alternative tendons (BR, FCR) may be used according to circumstances. An additional muscle unit (FDS, PL, EIP or EPL) can be connected to the lumbrical tendon. The next step is to activate the toe extensors by connecting them to ECRL and ECRB. Alternatively finger extensors can be used in fresh cases. Toe flexors are activated using FPL if available and with

Figure 6 X-ray shows the position of the transplant in a patient number 6 with movable carpus. Reproduced with the permission of Elsevier from Textbook: Surgical Techniques in Orthopaedics and Traumatology, Elsevier 2001,Chapter 55-390-B-10; Functional restoration of the no-finger hand.

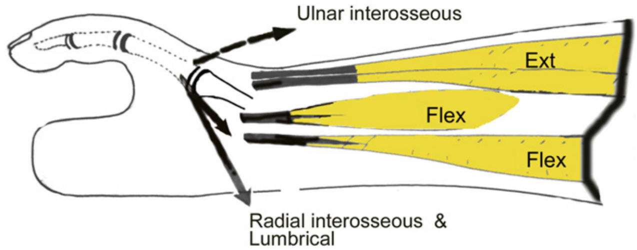

Figure 7 The schematic drawing shows the extrinsic muscles (yellow colour) which are used for toe extension and flexion. Additionally the 3 intrinsic tendons need activation with sound motors. Usually APL is used on ulnar side and FDS IV on radial side to interosseal tendons and PL for lumbrical function.

another superficial flexor tendon. In addition a temporary K-wire is used to fix the DIP-joint of the second toe into extension and the adjustment of long flexor tendon tightness is done after fixation. The extended tip of the neo-thumb is better than one with flexion contracture. One must remember that the short flexor of the toe is more important in thumb-like function and even a tenodesis between the flexors can be done to prevent from flexion contracture of the toe tip.

Microsurgical reconstruction

Revascularization is done anastomosing the radial artery to the longest artery of the toe-graft. Similarly the vein system is anastomosed to the cephalic vein. According to circumstances other vessels are repaired, for example when using a larger wrap around-flap for post side another superficial vein helps in preventing from venous congestion of the flap. Also ulnar or interosseal arteries may be used as donor vessels if they are more appropriate in length than the radial artery.

Sensory reconstruction is very important and for that purpose a part of the median nerve is sutured to plantar toe nerves. Radial sensory nerve is sutured to the dorsal toe nerves. Sometimes all graft nerves have to be sutured to the branches of the superficial radial nerve.

Skin coverage

The web contouring and skin closure and possible skin grafting are done as the last step. The island hemipulp flap is sutured into optimum location on the post side. The web is created from three components: the plantar skin flap of the toe graft, the hemipulp flap and the original skin of the stump. The amount and quality of the glabrous skin, which has remained at the stump, will dictate the need for a hemipulp flap.

The aim is that the new web and the proper pinching surfaces are covered with a durable glabrous skin with a possibility of adequate sensory recovery after nerve connections.

Longitudinal dorsal and volar skin flaps at distal antebrachial stump may be mobilized in order to get better quality skin into web area and achieve maximum mobility for the 'neo-thumb'. In such a case the secondary defects at ulnar border can be covered with free split skin grafts.

Primary closure of the foot is essential without skin grafting at first web to prevent from the later problems of the donor site. Only a small full thickness skin graft may be used at the hemipulp donor site.

Postoperative care

The postoperative monitoring is identical with usual toe-transfer cases. The skin temperature and vitality are checked frequently (every hour) for 2—3 days and then less frequently up to one week.

The gentle exercises using active motion of the neo-thumb can be started after one week under the therapist control. The detailed knowledge about rearranged muscle functions is discussed with the patient and he is carefully guided to use preoperatively well trained forearm muscles to find the new thumb functions first qualitatively. ECR muscles can achieve some extension movement and that is carefully guided in the presence of surgeon and hand therapist. FPL is often able to produce short flexion activity but there is always difficulty maintaining the flexed position without sensibility. A gentle active movement is encouraged from the beginning. After two-three weeks when wounds start to heal the flexion maintenance can be tried against another normally feeling skin area; for example around patient's contra lateral finger. The feed-back information about the used pressure and force, which is induced by the neo-thumb, can be transmitted via normally feeling body part and the power regulation can be more precise during exercises (contra lateral feedback).

A dynamic extension splint (Fig. 8) is very important, while the aim is to achieve an easily opening thumb and a flexion contracture should be avoided carefully during the rehabilitation.

Extension splint should be used starting from one week until 2—3 months. Simultaneously the flexion position of MTP-joint is encouraged with the splint. Both active flexion and active extension exercises are necessary but extension training directed to PIP joint is most important during the first three months. In typical case the sensibility will return in 5—6 months postoperatively. The good use of the reconstructed grip is dependant on its necessity. A motivated

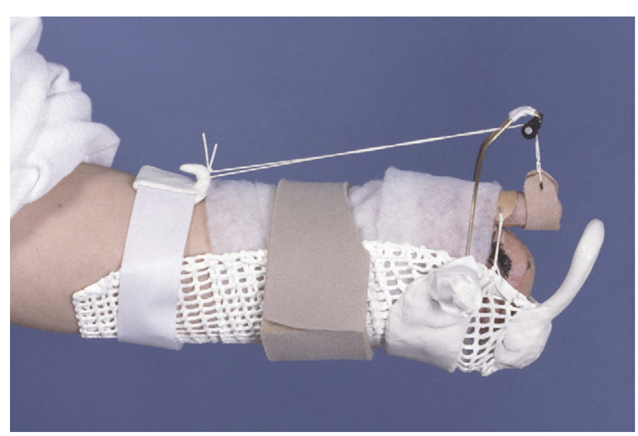

Figure 8 The postoperative dynamic splint is used for enhancing the extension and preventing the claw deformity for 2—3 months.

amputee will use it very regularly and achieves an acceptable prehension in one year after operation.

Patients and methods

The goal for the study was to find out the long term results of grip reconstruction in patients with a traumatic wrist level or distal forearm amputation. Both the achieved hand function and donor site defect were evaluated.

There were a total of 12 posttraumatic hand amputation patients in the series. A similar type of operation was done in one child with a bilateral congenital acheiria and he was included into the study.

All of the patients were operated on by the senior author between 1983 and 2000. One of the operations was done in Hungary and one in Sweden. A questionnaire was sent to 12 patients excluding the Hungarian patient who was lost at follow up. A clinical follow up study was done to 11 patients meeting the inclusion criteria. The patient's charts and x-rays were examined collecting information about the patient's general health, the injury, reconstructive surgery itself and the rehabilitation period.

Injuries and primary treatment

The primary care for the injuries was mostly given in local hospitals and the patients were referred to the reconstructive unit at a later state. Only one attempted replantation had been made. The injuries happened in a 14 year period between September 1981 and February 1995. The interval between the injury and the reconstructive procedure was an average 10 (3–32) months (Table 2). There were four crush and five explosion injuries (Table 1). One patient had an electrical burn injury of both forearms and one had a circulating saw injury. In four cases (patients 1, 5, 7 and 8) there was an injury of both upper extremities and two patients (number 1 and 4) lost their vision at the same time in an explosion injury. Patient no 1 had an amputation of 1st and 5th ray and a median and radial nerve injury. Both his nerve injuries were reconstructed with grafts and thumb with a toe-transplant. Patient no 5 had an amputation of 1st to 4th rays with only poorly functioning 5th ray left in the other hand. Patient no 7 had an electric burn injury causing bilateral antebrachial amputation with a short stump. Patient no 8 had a metacarpal hand type amputation on the other side. Seven of the injuries were covered by workman's compensation.

Patients

There were 3 women and 10 men (Table 1). The age of patients at the time of the injury averaged 28 y (16–49 years). All except patients no 8 and 13 were right handed and there were five dominant hand injuries. Four of the patients were smokers and all of them continued smoking after the reconstruction.

Questionnaire

The Tamai score was designed to evaluate hand function after replantation.[18] It consists of a questionnaire and a

Table 1 Preoperative data

Patient no	Age at injury (y)	Sex	Injury type	Level of amputation	Other injuries	Injury enviroment	Follow-up months
1	19	male	Blast	2	Severe injury in the other hand[a] Lost vision	Military	275
2	16	female	Crush	2	None	Work	268
3	26	male	Cirlulating saw	3	None	Work	
4	30	male	Blast	2	Lost vision	Work	261
5	49	male	Blast	3	Severe injury in the other hand[b]	Work	252
6	33	female	Crush	1	None	Work	246
7	49	male	Electric burn	4	Similiar amputations in both extermities	Work	241
8	17	male	Blast	2	Severe injury in the other hand[c]	Home	202
9	21	male	Blast	2	None	Home	198
10	18	male		1	None		
11	28	male	Crush	4	None	Work	182
12	33	female	Crush	3	None	Work	135
13	[d]	male	[d]	2	[d]	[d]	
Average	28						226

Level of amputation: 1 = movable carpus, 2 = amputation at radiocarpal joint, 3 = amputation proximal to DRU joint, 4 = short antebrachial stump.

[a] I and V ray amputation and median nerve injury.

[b] I-IV CMC level injury with only poorly functioning V ray left.

[c] metacarpal hand type amputation.

[d] bilateral congenital acheiria.

Table 2 Operation data

Patient no	Interval to reconstruction (months)	Toe artery	Recipient artery	No of nerves recontructed	No of tendons reconstructed	Operation time (hours)
1	15	1-2 DMTA, 1-2 PMTA	A.ulnaris	4	6	11.5
2	32	1-2 PMTA	A.radialis	4	7	10
3	8	1-2 DMTA	A.radialis	3	7	10.1
4	12	1-2 DMTA	A.radialis	4	7	10
5	7	1-2 DMTA	A.radialis	4	7	10.25
6	7	1-2 DMTA	A.radialis	4	7	10.3
7	11	1-2 DMTA	A.ulnaris	4	7	11.5
8	4	1-2 PMTA, 1-2 DMTA	A.radialis	4	7	12
9	3	1-2 PMTA	A.radialis	4	7	11.66
10	17	1-2 PMTA, 1-2 DMTA	A.radialis	4	7	14
11	3	1-2 DMTA, 2-3 PMTA	A.radialis, a.ulnaris	4	6	12.8
12	6	1-2 DMTA	A.radialis	4	7	11
13	162	3-4 PMTA	A.radialis	4	7	14.4
Average	11[a]					11.5

DMTA = dorsal metatarsal artery, PMTA = palmar metatarsal artery.
[a] excluding patient no 13.

clinical examination. The questionnaire contains questions about activities of daily living, specific problems concerning the replant, cosmetic outcome, satisfaction towards the operation and job status. We translated the Tamai score questionnaire in Finnish and modified the ADL section giving the patients a six grade option for each question. The questions concerning the replant were converted to questions of the toe transplant. The questionnaire also contained questions concerning the donor foot.

Clinical follow-up examination

Of the 13 patients meeting the inclusion criteria 12 returned our letter and 11 of those agreed to attend the follow-up visit. All the patients attending the follow-up visit were examined by an independent observer, the second author. An X-ray study taken from both hands and feet and a clinical evaluation of the patient was performed. We measured secondary parameters such as pinch, sensation, wideness of grip and mobility of the transplanted toe. To assess function of the hand we used the Sollerman hand function test.[19] To evaluate donor site defect and related problems we used the AOFAS scoring for forefoot.[20]

At the follow up visit we asked the patients 11 questions about how the hand with the toe-transplant functioned in activities of daily living. The patients were asked to rate their answers into four categories giving points from 1 to 4, total score thus ranging from 11 to 44 points. No complaint gave four points; minor complaint gave three points; moderate complaint gave two points and severe complaint gave one point. We asked for handling of small objects, strong gripping, strong turning, carrying objects, picking up objects from a pocket, getting dressed, getting washed up, managing oneself urinating and defecating, coping with work assignments, handling coins and key-grip.

Sollerman hand function test

Dr. Christer Sollerman (Gothenburg, Sweden) introduced his test in 1980. It was designed to evaluate grip function so disabilities of shoulder or elbow do not interfere with the test result. The test has 20 different tasks to evaluate 7 different forms of grip. In addition to time limits completing the tasks points are given on the quality of grip. Each test is evaluated with points ranging from 0 to 4. Hence the total score is between 0 to 80 points. Normal dominant hand should achieve 80 points and non-dominant hand 77—80 points. The tasks are done either single handed or the other hand has a distinctive assistant role. Both hands are tested. The test has a great interexaminer reproducibility.

AOFAS score

Kitaoka published a scoring system for disorders of the Hallux Metatarsophalangeal-Interphalangeal region. It consists of a questionnaire and a clinical examination. We chose this scoring systems since it can be anticipated that removing second toe might lead to problems about the forefoot like hallux valgus deformity.

Results

All of the 12 patients who received our questionnaire returned the letter. The follow-up time for the 11 patients examined according to study protocol is on average 212 months (17 years 8 months) ranging from 77 to 275 months. That is ample time to achieve full recovery and especially to adapt to the newly reconstructed hand. The time is also long enough to evaluate possible long term donor site defects. Patient no 13 had his fourth toe transplanted and in all others the second toe was used. Patient no 13 is excluded from data analyses of secondary parameters because of the nature his defect.

Comments on operations

Mean operation time was 11.5 hours. All the operations were done with one team approach. Operation details are presented in Table 2. There were no failures or emergency re-operation due to vascular problems (Table 3).

Pinch function

The key pinch ranged from 2 to 10.5 kg averaging 5.3 kg (Table 4). The pinch was 79 (25—175) % from that of the contra lateral hand. It must be kept in mind that patients no 1, 5, 7 and 8 had a severe injury to the contra lateral extremity as well. The key pinch for patient no 13 was 0.5 kg but a flexion deficit of the transplanted toe limited the pinch grip. Adding the width of the measuring devise increased the grip to 3.5 kg: s.

Range of motion and wideness of grip

The second (or fourth) toe has a small distal and intermediate phalanx and it is difficult to measure reliably the movement or position of the DIP -joint. That's why the DIP and PIP —joints were considered as one IP -joint. The active movement of the transplants IP —joint averaged 41° (20—65°). That was 57% (36—93%) of the movement of the contra lateral thumb excluding patients no 1, 5, 7, and 8 with bilateral defects. The extension lag of the IP -joint averaged 28° (0—65°). The MTP —joint active movement of the transplant averaged 34° (15—55°). It was 77% of the movement of contra lateral thumb again excluding the patients with bilateral hand defects. The total range of movement (Fig. 9) averaged 75° ranging from 40° to 105° (Table 4). Patient no 13 had a 20° active motion of IP-joint, a 30° extension lag of the IP-joint and a 95° total range of motion

Measuring the wideness of grip in a reliable and reproducible way is difficult. The measuring points have to be the same for each patient. That is why we chose to measure the wideness of grip from the edge of the nail of the transplant to the opposing surface and on the other side from the edge of the nail of the thumb to the edge of the nail of the index finger. On the side of transplant the wideness of grip averaged 40 mm ranging from 15 mm to 63 mm. On the other side the wideness of grip averaged 146 mm, ranging from 130 mm to 167 mm, again excluding the patients with bilateral defect. Patient no 13 had a 43 mm wideness of grip on the reconstructed side.

Sensory function

The sensation in general was poor in the transplanted toes. The static or dynamic 2PD was ≤10 mm in only patients 7 and 8. Interestingly patient no 7 had most complaint of poor sensibility. The static or dynamic 2 PD on the opposing surface of the transplant was >10 mm in all of the patients. We also used the Semmes-Weinstein filaments to evaluate sensation (Table 4). In our opinion the filaments seemed to be more reliable a way of examining the sensory function than the 2PD. Four out of ten of the opposing surfaces tested recognized f3.61 filament while only two of the transplants did so. Five transplants recognized j4.31 and three recognized t6.65 filament. One of the opposing surfaces didn't even recognize the t6.65 filament, two recognized t6.65 and the rest recognized the j4.31 filament. All of the opposing surfaces except patients no 5 could make a distinction between a sharp and blunt touch. The results for the patient no 13 are as follow: transplant j4.31, opposing surface t6.65.

Table 3 Complications and secondary operations

Patient no	Complications: Hand	Complications: Foot	Flap survival	Emergency re-operations	No of secondary operations: Hand	No of secondary operations: Foot	The complication or secondary operation performed
1	No	No	Yes	No	2	0	Skin plasty, tendon transfer[a]
2	Yes	No	Yes	No	0	0	Superficial infection
3	No	Yes	Yes	No	0	1	Wound revision + FSSG
4	No	Yes	Yes	No	1	0	DVT, tendon transfer[a]
5	No	No	Yes	No	1	0	Tendon transfer
6	No	No	Yes	No	0	0	
7	No	Yes	Yes	No	0	1	Wound revision + FSSG
8	No	No	Yes	No	0	0	
9	No	No	Yes	No	4	0	Artrodesis, tendon transfer x2, osteotomia
10			Yes	No			
11	No	Yes	Yes	No	0	4	Wound revision x4 + FSSG
12	No	No	Yes	No	1	0	Z-plasty and tenolysis
13	Yes	Yes	Yes	No	0	1	Superficial infection, foot wound revision and closure psi

FSSG = free split skin graft, DVT = deep venous thrombosis, psi = per secundam intentionem.
[a] patient had a traumatic dislocation of the toe-transfer MTP-joint and ECU tendon was transferred to augment ulnar aspect of the joint.

Table 4 Objective results

Patient no	Key pinch (kg): transfer	Key pinch (kg): control	S-W filaments: transfer	S-W filaments: opposing surface	S-W filaments: control	TAM: transfer	TAM: control	Sollerman score: transfer	Sollerman score: control	AOFAS score
1	3	2[a]	f3.61	j4.31	t6.65[a]	105	80[a]	22[a]	46[a]	95
2	9.5	9	j4.31	f3.61	f3.61	55	125	62	79	75
3										
4	4.5	13	t6.65	j4.31	f3.61	85	140	17[b]	57[b]	80
5	10.5	6[c]	t6.65	no	t6.65[c]	60	20[c]	26	33[c]	78
6	3	7	j4.31	f3.61	d2.83	90	100	56	78	100
7	2	no control	j4.31	j4.31	no control	40	no control	21[d]	2[d]	57
8	10	2[e]	j4.31	t6.65	k4.56[e]	115	0[e]	76	56[e]	100
9	3	11.5	j4.31	f3.61	f3.61	50	135	46	80	95
10										
11	3.5	9	t6.65	t6.65	d2.83	95	120	29	80	80
12	3.5	6	f3.61	f3.61	d2.83	50	125	24	77	100
13	0.5	0.5[f]	j4.31	t6.65	j4.31[f]	95	30[f]	16	32[f]	78
Average	5.3					75		36		85

S-W filaments = Semmes-Weinstein filaments. Opposing surface = the contact area for the toe-transfer in pinch. TAM = total active motion.

[a] the patient lost vision at the injury and the control hand has an amputation of 1. and 5. rays and median and radial sensory nerves reconstructed with grafts. The thumb has been reconstructed with a second toe transfer.

[b] the patient is blind.

[c] the control hand has a CMC I-IV level amputation with only poorly functioning V ray.

[d] the other extremity has similar level amputation without any grip reconstruction.

[e] the control hand has a metacarpal hand type amputation.

[f] bilateral congenital acheiria. The control is a second toe transfer. This patient was excluded from the reported average.

The Sollerman hand function test

The Sollerman hand function test score averaged 36 (16 to 76) points (Table 4). The score of the control hand averaged 56 (2—80) points. Patient no 7 had bilaterally a short antebrachial stump. The reconstructed site scored 21 and the side left untouched scored only two points. Other poor results on the control side were for patients with either bimanual defect or loss of vision (patients 1, 4, 5, 8 and 13). Two examples of the tasks included in the Sollerman hand function test are demonstrated in Fig. 10a and b.

Donor site

The AOFAS test scored average 85 points ranging from 57 to 100 points (Table 4). The questionnaire part of the test averaged 53 points (range 24 to 60 points) of a maximum of 60 points. The weight bearing axis had chanced and four patients had slight hallux valgus deformity. Patient no 2 had distinct hallux valgus deformity and hammering of the minor toes. The patients with shifted weight bearing axis scored worse in AOFAS test (average 73.8) compared to those with no hallux valgus deformity (average 95).

Subjective: hand

In general the lack of or poor quality of sensory function was not a major complaint (Table 5). Cold intolerance was a common complaint with the hand. It was a severe complaint for patients no 5 and 9, a moderate complaint for patients no 1, 7, and 12. The rest reported it to be either a minor of no complaint. We asked for social acceptance i.e. how the patients felt other people's reactions towards their injured hand. Only patient no 12 reported severe complaint over other people's reaction. Two patients (patients no 7 and 10) used a cosmetic prosthesis in the presence of strangers. Patient no 7 used a myoelectric prosthesis occasionally. We asked for satisfaction of the cosmetic outcome (Fig. 11) of the hand on a Visual analogue scale. 100 being the best and 0 the worst result the patients averaged 64 (25—93). The two patients (patients no 1 and 4) with loss of vision were not asked to rate the cosmetic result on a VAS scale. Our own ADL questionnaire averaged 27 ranging from 12 to 43 points. Of the specific questions asked (scale 1—4) the strong gripping, getting washed up and managing oneself urinating and defecating scored best averaging 2.9, 3.4 and 3.3 respectively. On the other hand handling small objects, handling coins and strong turning appeared more difficult averaging 1.8, 1.8 and 2.1 respectively. The ADL section of the Tamai scoring system averaged 7, 9 (2, 75—14, 25) points. There is a clear correlation between the two ADL questionnaires (Spearmann r = 0.887). The Tamai questionnaire rates satisfaction into five categories giving points from 0 to 20. Satisfaction averaged 15 ranging from 20 (highly satisfied) to 5 (poorly satisfied). There were 8 out of 12 who reported to be either highly or fairly satisfied (Fig. 12) with the outcome of the surgery (Table 6). All of the patients would have selected the toe-transfer operation again. Both the

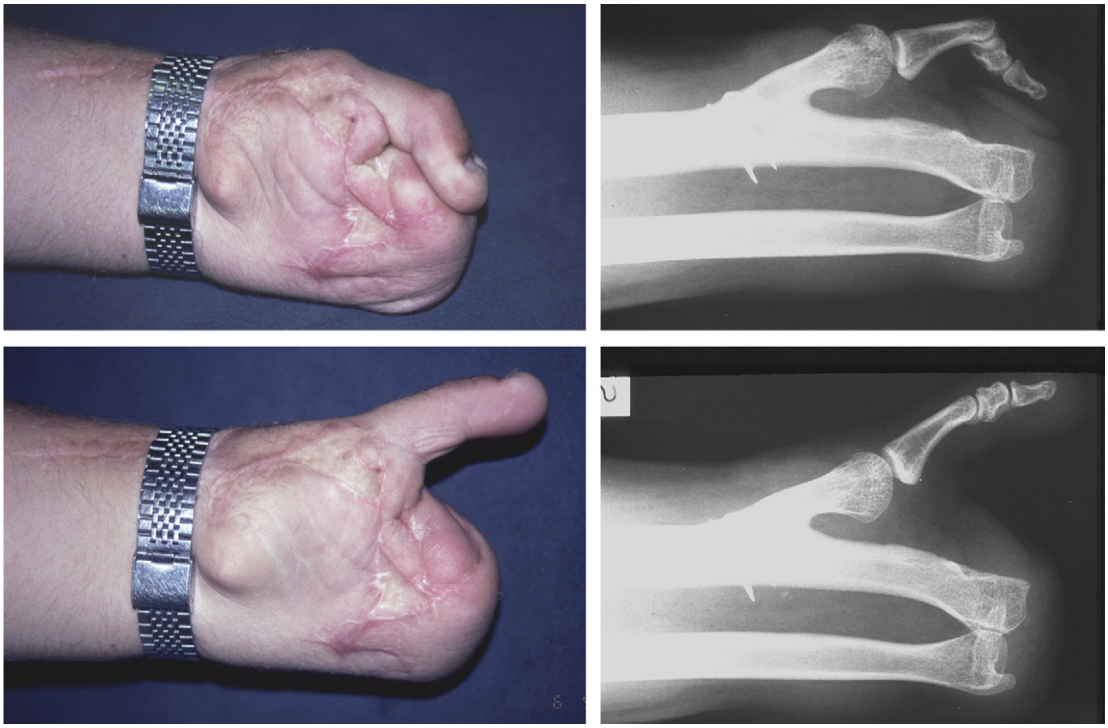

Figure 9 Patient no 8 has a good mobility here shown clinically and radiologically. The X-ray is also showing the typical configuration of the reconstructed thumb. Reproduced with the permission of Elsevier from Textbook: Surgical Techniques in Orthopaedics and Traumatology, Elsevier 2001,Chapter 55-390-B-10; Functional restoration of the no-finger hand.

ADL questionnaires correlated with patient reported satisfaction (Our ADL: Spearmann r = 0.730, Tamai ADL: Spearmann r = 0.749).

Subjective: donor site

Overall the transfer of the second toe seemed to be well tolerated even in long term follow up. Patient no 7 reported moderate complaint in both walking and running (Table 5). Patient no 4 had also moderate complaint in walking and patient no 11 in running. The rest reported no or minor complaint in walking or running. Patient no 4 had painful neuroma but the complaint was only minor. General satisfaction for the donor site was good with only patients no 7 and 11 reporting dissatisfaction. Cold intolerance was present and patients no 5, 7, and 12 reported moderate complaint over it. The rest had either no or minor complaint. Pain at rest was a major complaint to patient no 7 and moderate complaint to patient no 11. The rest didn't have any pain at rest.

Complications and late corrective procedures

There were no serious complications other than one deep venous thrombosis in patient no 4 (table 3). In early postoperative phase there were minor problems in wound healing in two hands (patients no 2 and 13) and in five feet (patients no 3, 4, 7, 11 and 13).

The new grip was not fully successful in all cases at the first attempt. In order for the pinch to be effective the toe transplant has to be aligned correctly. The contact point (pulp of the toe) during flexion of the transplant has to be directed towards a firm opposing surface with good quality skin. The extension arch must be adequate to open the newly created web space widely enough for the most common objects to fit in.

In our series there were four patients with late corrective procedures. Patient 9 had four corrective operations including fusion of the remaining carpal bones with the radius, twice an extensor tendon tenolysis and just recently a corrective osteotomy of the transplant with tendon relocation on the dorsal aspect of the MTP-joint. Patient no 12 had a Z-plasty of the web space and an extensor tendon tenolysis. Patient no 5 had a tendon transfer. Both blind patients (numbers 1 and 4) accidentally injured their MTP-joints in an accident equal to skier's thumb. The joint stability was restored and augmented with an ECU transfer to the ulnar aspect of the joint. Patient 1 had also a resection of poor quality skin and local skin plasty on the opposing surface of the transfer.

Discussion

The technique described to rehabilitate the victims of hand amputation is useful for both unilateral and bilateral amputees. The advantage over other microsurgical techniques using multiple toe transplantations is that a direct connection of healthy tissues at operation site is possible. The microsurgical success may be achieved more easily when no nerve or vessel grafts are needed. Also the tendon coupling at almost healthy tissue site allows good functional result. The donor site is also minimally affected

Figure 10 a and b. Patient no 8 has a good powerful prehensile grip with normal pro-supination. He got the best results in Sollerman test.

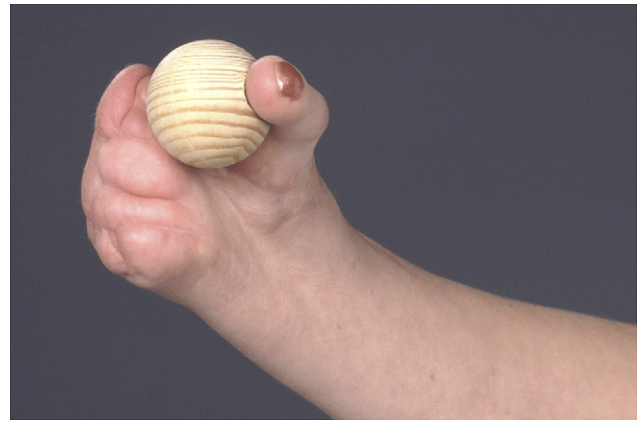

Figure 11 The cosmetic result of patient no 6 shown clinically. Reproduced with the permission of Elsevier from Textbook: Surgical Techniques in Orthopaedics and Traumatology, Elsevier 2001,Chapter 55-390-B-10; Functional restoration of the no-finger hand.

while only a second toe with a hemipulp flap from the great toe is needed.

The described microsurgical autogenous reconstruction and means of rehabilitation is directed to wrist and distal forearm amputees. The best length of the forearm stump for this procedure is a radiocarpal-joint level amputation. In this series the two shortest stumps reconstructed have been 14 cm and 17 cm respectively. The reconstructive procedure is more difficult in a short stump especially when many months have elapsed after the trauma and the muscles have become retracted and scarred. The timing should be either immediately in primary injury phase

Table 5 Subjective results

Patient no	Hand						Foot			
	Hypoestesia	Cold intolerance	Social acceptance	Satisfaction (0–20)	Our ADL (11–44)	ADL from Tamai Scoring system (0–20)	Walking	Running	Cold intolerance	Pain at rest
1[a]	3	2	4	20	32	10	4	4	3	4
2	4	4	2	20	44	12.25	4	4	3	4
3				15		4.75				
4[a]	3	3	4	15	27	7.75	2	4	4	4
5	4	1	2	5	18	2.75	4	4	2	4
6	3	4	4	10	26	9.25	4	4	4	4
7	2	2	3	15	12	4.75	2	2	2	1
8	4	4	4	20	38	14.25	4	4	4	4
9	4	1	4	20	26	7.5	4	4	3	4
10										
11	2	3	3	10	21	2.75	3	2	4	2
12	3	2	1	10	19	4.75	4	4	2	4
13	4	4	4	20	34	13.5	4	4	4	4
Average				15	27	7.8				

4 = no complaints, 3 = minor complaint, 2 = moderate complaint, 1 = severe complaint.
Satisfaction: 20 = highly satisfied, 15 = fairly satisfied, 10 = satisfied, 5 = poorly satisfied, 0 = not satisfied, would not want the operation again.
[a] both patients lost their vision at the trauma.

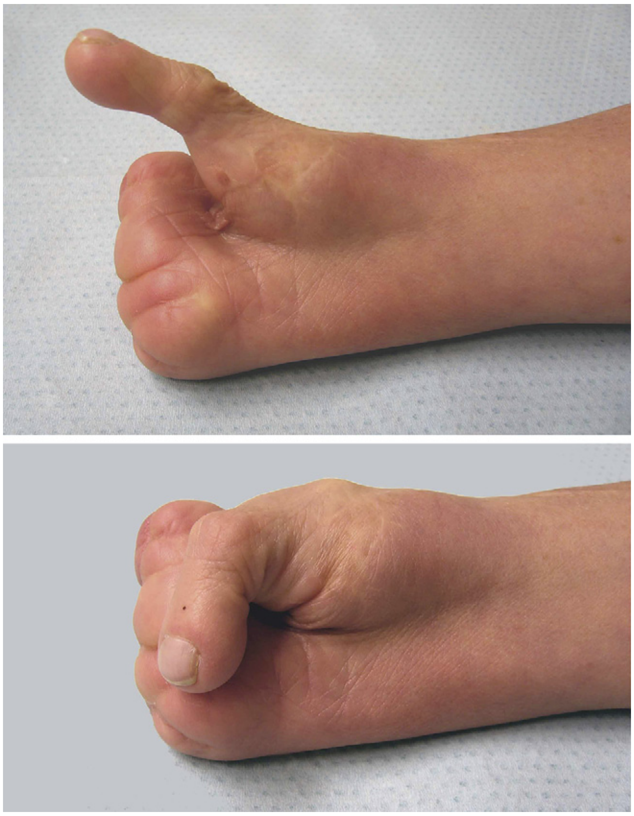

Figure 12 The movable neo-thumb has enabled patient no 6 to continue in manual labour.

or as early as possible for best results. Sometimes it is good to remember this technique already in emergency replantation in some special injuries, when there is only one usable finger left but the hand itself is completely destroyed. When one almost intact detached finger is available for this reconstruction then a longer 'neo-thumb' (compared to second toe) can be created.

The limitations of our study are the small patient material and the distribution of patients in several smaller categories. The results in group with wrist level amputations are quite comparable. However the infrequent need of this type reconstruction makes the learning and experience to produce ideal reconstruction pattern difficult in every individual case.

The results achieved in this series were influenced by many different factors. The pinch grip is small but powerful enough to make a new thumb useful in daily use. The power in this new pinch grip is dependant on use and practise and a pinch gauge measurements comparable to normal key pinch can be achieved in best cases. It can be compared to the power of the normal thumb flexing against proximal phalanx of completely bent index finger. Six of thirteen patients in the series were employed or worked normally. The results from our ADL questionnaire correlated with

ADL section of the Tamai's score and patient satisfaction (Table 6). We feel that the general activity of the patient was related to satisfaction after reconstruction. The Sollerman hand function test gave good values with the patients who were at work and used the hands regularly. There were five bilateral amputees, who experienced this small new gripping ability very important although the functional capacity was rather week. The patient (no. 7) who had an electric burn induced bilateral proximal forearm amputation scored markedly better with this pinch reconstruction compared to nonreconstructed stump. Two blind patients had inferior results in Sollerman test. Their results were influenced apparently by the loss of vision but they experienced however great benefit from the 'neo-thumb' and their ADL scores were above average. These blind patients cannot get any functional advantage of prosthetic hand. In normal sighted patients the fitting of a prosthetic hand after this type 'neo-thumb' reconstruction is possible and a new thumb can be used to steer the micro-switches to activate the artificial limb functions even more precisely than a myoelectric steering.[21] Less optimal results correlated to the type of injury (electrical burn pat. no. 7) or to the short

Table 6 Score results

Patient no	Sollerman test score (0–80)	Our ADL (11–44)	ADL from Tamai Scoring system (0–20)	Satisfaction (0–20)
1	22	32	10	20
2	62	44	12.25	20
3			4.75	15
4	17	27	7.75	15
5	26	18	2.75	5
6	56	26	9.25	10
7	21	12	4.75	15
8	76	38	14.25	20
9	46	26	7.5	20
10				
11	29	21	2.75	10
12	24	19	4.75	10
13	16	34	13.5	20
Average	36	27	7.8	15

length of the antebrachial stump (patients no. 7 and 11). Comparing the results with other reconstruction attempts is difficult. Possibly more web space can be achieved in a modification where the distal radius would be completely resected and the ulna was used as opposing post.[8] However, the firmness and stability of the grip may be compromised in such a reconstruction. This seems evident since the patients with intact DRU-joint (patients 1, 2, 4, 6, 8, 9 and 13) scored better both subjective and objective.

Other modifications include multiple toe-transfers.[22,23] The use of these options is dependant on local expertise and facilities and patient preference. The results may be better but the needed reconstruction can be very difficult especially due to bad tissue conditions at the distal stump. Also the acceptance to donate multiple toes is often found difficult among many patients. The cultural and religious as well as individual differences will influence into selection and possibilities of rehabilitation after wrist or distal forearm amputations. In our opinion the human hand transplantation is not at present an acceptable method to rehabilitate otherwise healthy amputee patients because of the adverse effects and need for continuous immunosupression therapy, which will risk the patients general health. To-day an autogenous grip reconstruction with described method remains still the safe option for the victims of severe amputation injuries. The need of this kind of reconstruction is becoming less frequent because these types of amputation injuries are replanted immediately in primary emergency situation. In cases where replantation is not possible our grip reconstruction is a good option with useful function and acceptable donor site morbidity.

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