TERO KOTKANSALO

Post-traumatic Grip Reconstruction with Toe Transfers

ACADEMIC DISSERTATION
To be presented, with the permission of the Board of the School of Medicine of the University of Tampere, for public discussion in the Auditorium of Finn-Medi 5, Biokatu 12, Tampere, on October 11th, 2014, at 12 o’clock.

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TERO KOTKANSALO

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ABSTRACT

The purpose of this study was to assess and report long-term results of post-traumatic grip reconstruction using microvascular toe transfers. The outcomes of this retrospective study were divided into primary (function) and secondary (physical parameters, satisfaction, cosmetic appearance, osteoarthritis etc.) and the methods of reaching them were divided into patient-reported (questionnaires), clinician-based (tests) and radiographic. The recipient and the donor site were evaluated separately. Further, the patient charts were examined to collect information about the injury, reconstruction and postoperative events.

Based on the patients treated by one of the supervisors of this academic dissertation, 97 patients fulfilling the inclusion criteria were identified. In addition, one hand of a patient who had had microvascular toe transfer to reconstruct congenital absence of the hand (acheiria) was included. Of the 98 eligible patients, 74 patients (75 hands, 80 feet, 85 transferred toes) attended the clinical follow-up forming the population of this study. The patient population was divided into four groups (presented in the articles I–IV) based on the need for targeted grip reconstruction of either the thumb, fingers, metacarpal or antebrachial stump according to the classification of no-finger hand (Vilkki 2001). The donor site consequences were reported from the whole patient population in article V.

The median and (range) of follow-up for the 74 patients was 16 years 7 months (31–358 months). There was a failure of one of the toes of a double en-bloc transfer, yielding a survival rate of 98.8%.

According to the questionnaires, the 41 thumb reconstruction patients considered most activities easy or quite easy and managed the ADL with no or minor complaints. Tests measuring function showed good results in the majority of patients. Patient satisfaction was high. The patients regained 63 % of key pinch and 84 % of grip strength (compared to the other hand). The mean for the cylinder grip width was 10 cm.

The fifteen finger reconstruction patients scored well in the tests measuring function and managed the ADL with minor difficulties. Key pinch regained to 100 % and grip strength to 46 % (compared to the other hand) with a median 28° TAROM of the transfer IP joint. Patients who had no fingers left did better with two, rather than just
one, toes transferred. Patients with no-finger hand could not be reconstructed to the same level of function as those with some finger function spared by the amputation.

The eight MC-hand patients executed the tests measuring function with slight difficulties. The ADL was managed with moderate complaints. Key pinch regained to a mean of 4.3 kg which was 40% of that of the control hand. All except one patient were either satisfied or highly satisfied with the outcome.

Despite the 11 AB-stump patients scoring inferiorly in the primary outcome measures, patient satisfaction was similar to the other transfer groups. Patients with amputation distal to DRU joint (n=5) scored better in the primary outcomes, were more satisfied and were more likely employed than those with amputation proximal to DRU joint (n=6).

According to the functional scores, 92% of the patients reported no or minor complaints and 83% of the patients received a good result at the donor feet. Sixteen feet were completely free of symptoms, and the rest had most often mild symptoms. Cold intolerance and pain during exertion were most often reported complaints. The toe transfer raised the risk of developing pathologically increased HVA.

Three patients, of the total 74, needed emergency re-operation due to vascular compromise of the transfer. Problems in the donor site wound healing resulted in more problems in walking and inferior functional recovery. Wound healing was compromised more often in patients who smoked or when the wound was closed with the help of STSG. A secondary operation to the recipient site was performed to a quarter of patients.

In conclusion, grip reconstruction was successful in most of the cases with high patient satisfaction. The donor site defect was overcome by the recipient site gain.
TIIVISTELMÄ

Tämän tutkimuksen tarkoituksena oli arvioida ja esittää tapaturman jälkeisen varvasiirteillä tehdyn oterekonstruktion pitkäaikaistulokset. Tämän taktakuvan tutkimuksen tulosmuutujat jaettiin ensisijaisiin (toiminta) ja toissijaisiin (fyysiset parametrit, tyvyvälys, ulkonäkö, nivelen kuluma jne.). Menetelmät, joilla näitä selvitettiin, jaettiin potilaslähtöisiin (kyselylomakkeet), tutkijalähtöisiin (testit) ja radiologisiin. Ottokohta sekä vastaanottava kohta tutkittiin erikseen. Tämän lisäksi potilastiedostoista kerättiin tietoa tapaturmasta, leikkauksesta, sekä leikkauksen jälkeisistä tapahtumista.


Seuranta-ajan mediaani ja (vaihteluväli) 74 potilaalle oli 16 vuotta 7 kuukautta (31–358 kuukautta). Yksi varpaista, joka oli osa 2–3 varpaiden komposiitti varvassiireetestä, menettiin, joten selviytymisuhde oli 98.8 %.

Käytettyjen kyselyjen mukaan 41 peukalorekonstruktio potilaasta kokivat useimmat toiminnot helppoiksi tai melko helppoiksi ja pärjäsivät päivittäissä askeleissa ilman vaivoja tai vähäisiin vaivoihin. Valtaosa potilaista sai hyviä tuloksia toimintaa mittaavissa testeissä. Potilasyvyväisyys oli hyvä. Avainotteen voima toipui 63 % ja puristusotteen voima 84 % (verrattuna toiseen käteen). Sylinteriotteen leveys oli keskimäärin 10 cm.

Nämä potilaat eivät kuitenkaan saavuttaneet samaa tasoa kuin potilaat, joilla oli jäänyt joitain sormia jäljelle.

Kahdeksan potilasta, joilla oli keskikämmenen tason amputaatio, suoriutuivat keskimäärin lievin vaikeuksin toimintaa mittaavista testeistä. Päivittäiset askareet tuottivat kohtalaisia vaikeuksia. Avainotteen voima oli keskimäärin 4,3 kg, mikä oli 40% toisen käden voimasta. Kaikki yhtä lukuun ottamatta olivat tyytyväisiä tai erittäin tyytyväisiä lopputulokseen.

Vaikka ne potilaat (11 kappaletta), joilla oli kyynärvarsitynkkä tason amputaatio, sai vatkin huonompia tuloksia ensisijaisissa tulosmuuttujissa, potilastyytyväisyys oli yhtä hyvä kuin muissa ryhmissä. Ne potilaat, joilla amputaatiotaso oli alemman kyynärvarsinivelen alapuolella (n=5) saivat parempia tuloksia ensisijaisista tulosmuuttujista, olivat tyytyväisempiä ja olivat todennäköisemmin työelämässä kuin potilaat, joilla amputaatiotaso oli alemman kyynärvarsinivelen yläpuolella (n=6).

Luovuttajajalan (n=80) toimintaa mittaavissa testeissä 92% potilaista kuvasi joko ei vaivoja tai vähäisiä vaivoja ja 83% potilaista saavutti hyvän tuloksen. Kuuressaista jalassa ei ollut mitään oireita, ja lopuillakin oireet olivat lieviä. Kylmänarkkuus ja kipu rasituksessa olivat useimmin esiintyviä oireita. Varvassirre lisäsi risiä poikkeavan suuren vaivaisenlunun kulman muodostumiseen.


Lopppäätelmänä voidaan todeta, että oterekonstruktio onnistui useimmilla potilailla ja potilastyytyväisyys oli hyvä. Siirteen vastaanottokohdan hyöty oli suurempi kuin luovuttajakohtaan aiheutettu haitta.
LIST OF ORIGINAL COMMUNICATIONS

The present study is based on the following articles, which have been referred to in the text by their Roman numerals (I–V)


ABBREVIATIONS

AB-stump  Antebrachial stump
ADL       Activities of daily living
AOFAS     American Orthopaedic Foot and Ankle Society
AdP       Adductor pollicis
CI        Confidence interval
CMC       Carpo-metacarpal
DIP       Distal inter-phalangeal
DRU       Distal radio-ulnar
F         Female
FDP       Flexor digitorum profundus
FDS       Flexor digitorum superficialis
FHL       Flexor hallucis longus
HV        Hallux valgus
HVA       Hallux valgus angle
IFSSH     International Federation of Societies for Surgery of the Hand
IMA       Inter-metatarsal angle
IP        Inter-phalangeal
K-wire    Kirschner wire
m2PD      Moving two-point discrimination
M2-DASH   Manchester-modified Disabilities of Arm Shoulder and Hand score
MC        Metacarpal
MCP       Metacarpophalangeal
MC-hand   Metacarpal hand
MHQ       Michigan Hand Outcome Questionnaire
MT        Metatarsus
MTP       Metatarso-phalangeal
LLFQ      Lower Limb Function Questionnaire
PIP       Proximal inter-phalangeal
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tr>
<td>TAROM</td>
<td>Total active range of motion</td>
</tr>
<tr>
<td>s2PD</td>
<td>Static two-point discrimination</td>
</tr>
<tr>
<td>SHFT</td>
<td>Sollerman hand function test</td>
</tr>
<tr>
<td>STSG</td>
<td>Split-thickness skin graft</td>
</tr>
<tr>
<td>S-W</td>
<td>Semmes-Weinstein</td>
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<tr>
<td>VAS</td>
<td>Visual analogue scale</td>
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1 INTRODUCTION

Prehension, the ability to approach, grasp and release an object, is the basic function of the hand (Moran and Berger 2003). The elemental requirements for prehension are stable support, usually the wrist but in more proximal amputations the forearm, and two opposing digits. At least one of the opposing digits should be able to move in opening and closing directions to allow objects to be fitted in between. They should have sufficient sensation and be free of pain. Complete amputation of several or all of the digits leaves the hand without such capability. When replantation is not possible or successful, microvascular transfer of toes should be considered to restore prehension.

The thumb participates in almost all forms of grip and, therefore, the loss of it severely disables the hand. The contribution of the thumb for hand function has been estimated as high as 40–50% (Strickland and Kleinman 1993). The minimum length of the thumb for adequate function is dependent on the condition of the other fingers. In case of intact fingers, thumb amputation at the level of IP joint or even proximal to it may be well tolerated (Moran and Berger 2003). Whereas, patients with thumb amputation proximal to the middle of the proximal phalanx will probably benefit from thumb reconstruction (O’Brien et al. 1978b).

The exact number and length of fingers for sufficient interaction with the thumb is not commonly agreed. Clearly the thumb opposing against the palm with no fingers is awkward. In the Vilkki classification, the prerequisites for finger reconstruction are sufficient thumb function (no need for thumb reconstruction) and at least two functioning or reconstructable finger MCP joints (Vilkki 2001). A single finger allows for, depending on its position and length, precision pinch, oppositional pinch or key pinch (Moran and Berger 2003). A more versatile tripod pinch is possible with a thumb and two opposing digits. In a hand with thumb but no fingers, reconstruction of this kind of tripod pinch is recommended since it offers enhanced lateral stability in key pinch, provides stronger hook grip and wider span grasp compared to a single digit reconstruction (Ma et al. 1996).

Michon and Dolich introduced the term metacarpal hand to the scientific literature (Michon and Dolich 1974). It was defined as a complete loss of all the digits or a hand with entirely or partially intact thumb, ‘thumb without fingers’. A true metacarpal hand (level B according to the Vilkki classification) with no functioning digital joints other
than the first CMC poses a challenge to restore the hand function. Left untreated, the hand can only press and push objects.

Post-traumatic wrist or forearm level amputation considerably restricts the possibilities of reconstruction. No functional elements of the hand are left and often the soft tissue, vascular, neural and tendon-muscle units are injured far proximally. There is still a multitude of tendon-muscle units in the forearm to motor a toe transfer. Vilkki presented in 1985 a technique where a three jointed second toe is transferred to the side of the radius to enable a simple pinching function (Vilkki 1985). This procedure was designed to improve the outcome compared to what was achieved with the Krukenberg’s operation (Krukenberg 1931). Despite the advances in the upper extremity prosthetics (Zlotolow and Kozin 2012), the sensory feedback from the transplanted toe and its opposing post are still unique and un-matched by prosthetic devices. Since the report of the first human hand allotransplant under the era of modern immunosuppression was introduced (Dubernard et al. 1999), it has been debated whether it is ethically justified to expose the patients to life-long anti-rejection medication and its possible risks.

The scientific literature covering patients with microvascular toe transfers has, so far, focused largely on reporting survival and physical parameters. Two studies using a control group, could demonstrate the benefit of thumb reconstruction compared to patients with thumb amputation left untreated (Chung and Wei 2000, Parvizi et al. 2012). Further, an improvement of function according to MHQ could be shown in the situation after thumb reconstruction when compared to patients’ recollection of the situation prior to the procedure (Fan et al. 2006). The outcomes after finger reconstruction have been described as high satisfaction (Leung 1980a), only 1/8 had minor difficulties in manipulating small objects and all substantially improved in function (Gordon et al. 1985). The function after MC-hand reconstruction was noted to be overall assessed good, with 82.6% of patients independent in ADL and Jebsen-Taylor showing below normal values with few exceptions (Williamson et al. 2001), and two patients reported general satisfaction with achieved function (according to MHQ) while executing the Jebsen-Taylor test 10–20 seconds slower than the control hand (Chung and Kotsis 2002).

No statistically significant difference could be detected in the LLFQ between patients who had donated a toe and control patients, or between the transfers used (12 great- and four second toes) (Chung and Wei 2000). In a prospective study setting, it was noted that each type of transfer (great toe, wrap-around, second toe) had caused distinctive alternations to the donor feet (Barca et al. 1995). They concluded that since the second toe transfer had no effect on the function or the outlook of the donor feet, it should be preferred. However, gait analyses have failed to show differences in the behaviour of the donor feet when tested pre- and postoperatively (Lipton et al. 1987) or between the donor and the control feet (Poppen et al. 1983, Yoshimura 1984).
2 REVIEW OF THE LITERATURE

2.1 History of post-traumatic thumb/finger reconstruction

2.1.1 Pedicled reconstruction

In 1900 Carl Nicoladoni, an Austrian surgeon, published the first technique of thumb reconstruction using a great toe (Nicoladoni 1900). Since operative microscopes or microsurgical instrumentations were not available at that time, the operation was done in a staged fashion. That is, soft tissues including the skin on the dorsum of the first MT and the long flexor and extensor tendons were connected to the hand in the first operation. In a few weeks new blood vessels grew from the hand to the skin and soft tissue of the flap to the extent that it could survive. In a second operation the great toe was finally detached from the foot and osteosynthesis was performed. The technique was further expanded to four- and five-digit reconstructions (Clarkson 1954) and refined to include secondary nerve reconstruction (Chandler and Clarkson 1958). However, the technique still remained cumbersome for the patient and the results were not predictable. Microvascular transfer of a toe has replaced the predecessor, pedicled transfer, in modern practice of reconstructive surgery. Still, in a situation of insufficient facilities, a pedicled transfer of a toe is a viable option (Riaz et al. 2003). The contribution of Nicoladoni for the later surgeons was the concept of transferring a functional unit to new location and thereby improving the overall situation.

2.1.2 Microvascular reconstruction

In 1966 Buncke et al. reported the first one-stage great toe-to-hand transplantation using “microminiature” vascular anastomoses (Buncke et al. 1966). The operation was done to a Rhesus monkey. That same year, the first clinical case of microvascular toe transfer was performed in the republic of China (Dongyue and Yudong 1979). A second toe was used for grip reconstruction in thumb position in a young patient who had had a traumatic amputation of all the digits of the hand. The results were published
13 years later, so their case is often neglected as the first of this kind. At that time, the second toe was considered too small to replace the thumb and it had a tendency of poor extension after the reconstruction.

Therefore, the interest turned to the great toe. Cobbett presented the first total great toe transfer for thumb reconstruction in 1969 (Cobbett 1969). The great toe provided a large contact area and similar arch of motion as the thumb. However, there were limitations considering the length of the transfer and the size discrepancy. That is, the length of the great toe was sufficient for reconstructions up to the level of the MCP joint but not for longer defects and the circumference of the great toe was larger than that of the thumb. Further, the donor site defect of resecting the great toe was thought to be greater than with other methods.

To address some of these issues, Morrison et al. introduced the so-called wrap-around flap from the great toe in 1980 (Morrison et al. 1980). It was essentially a free neurovascular skin flap, including the nail, from the plantar and fibular side of the great toe which was wrapped around a non-vascular iliac crest bone graft. This method produced better size match and diminished the donor site problems. It was, however, immobile and had problems with instability of the pulp and the bone graft resorbing and fracturing. This method was refined by harvesting the skin from both sides of the great toe leaving central weight bearing area intact (Tsai and Falconer 1986). The problems with the bone graft were dealt with by including to the transfer a distal terminal phalanx of the great toe (Hashimoto et al. 1986).

Wei et al. presented the next major step in microvascular thumb reconstruction in 1988 (Wei et al. 1988). Their method was called the trimmed-toe and it meant trimming, or excising a part, of the great toe from the tibial side. This allowed a very good size match and appearance while maintaining IP joint motion. In addition, the problems with bone grafts were solved since none was needed. This ideology of trimming the transferred toes spread to finger reconstruction as well.

For grip reconstruction after traumatic amputation of fingers, a number of options are available. A single second toe transfer is widely used for a single finger reconstruction. An isolated third toe can be used in cases were second toe is unavailable, needed for thumb reconstruction or saved because the great toe is used as a transfer (Wei 2005). In a situation where all the fingers are amputated, it is preferred to transfer at least two toes to enable a more stable tripod pinch between a thumb and the transferred toes, to enhance lateral stability, to provide stronger hook grip and to provide a wider span for grasping large objects (Ma et al. 1996). Tsai performed the first combined second and third toe transfer for adjacent finger reconstruction proximal to the digital web in 1973 (Tsai 1979).
In 24.4.1978, the first microvascular toe transfer in Finland was performed by a team of surgeons led by Professor Kauko Solonen (Solonen et al. 1982). The first patient had injured her right dominant hand in a combine harvester accident 20 months prior to the reconstruction. In an 8 hour operation, a second toe of her right foot was transferred to thumb position. Three months later, in a scheduled operation, the volar nerves of the transferred toe were reconstructed with sural nerve grafts. After a 28 y 10 month follow-up, the patient was very satisfied with the transfer and could perform almost all the activities of daily living without difficulties.

2.2 Classifications of traumatic amputations of the hand

In general, traumatic amputations can be divided on the basis of the mechanism of injury, the level of amputation and the number of digits amputated. Usually the level of amputation refers to skeletal rather than soft tissue injury. An exception is an avulsion amputation of soft tissues usually from a single finger or a thumb. This injury type is called ring avulsion, since the most common mechanism is that of a ring getting caught and pulling the soft tissue off the (ring) finger. The amputations can also be classified simply by the detached body part, namely finger, thumb or hand. More complex classifications try to address all the different injured tissues to better guide in reconstruction and in estimation of the outcome.

2.2.1 Thumb and fingers

The Replantation Committee of the International Society of the Reconstructive Microsurgery has published *Definition and classifications in replantation surgery* (Biemer 1980). In it, hand amputations were classified into five zones, first three of which involve the thumb and fingers. Zone 1 refers to the level of (distal) IP joint, zone 2 refers to PIP joint (finger) or MCP joint (thumb) and zone 3 refers to the base of the proximal phalanx (finger) or the MC bone (thumb). Zone 4 (Midhand amputations) equals to the MCP joint level of the fingers and zone 5 (Hand amputations) equals to metacarpal and wrist level. The next classification divided finger amputations into five zones according to the anatomy of blood vessels and flexor tendons (Tamai 1982). The borderline between hand and digit was placed at the level of superficial palmar arterial arch. Finger and thumb amputations can also be classified according to the flexor tendon zones (Kleinert and Verdan 1983).
Morrison et al. introduced the first classification only for thumb amputations in 1984 (Morrison et al. 1984). They divided the thumb amputation into soft tissue or segmental (distal), subtotal (where function of the first CMC joint and thenar muscles remain) and total thumb loss. Subtotal was further divided into distal (intact MCP joint) and proximal (absent MCP joint). Leung divided thumb amputations into four types (Leung 1985). Type I was an amputation within 1 cm of MCP joint (distal or proximal); type II at metacarpal level (with intact thenar muscles); type III at first CMC level (loss of thenar muscles) and type IV total loss of thumb and one to two radial fingers (hemi-hand). Merle presented his seven-stage classification in 1991 (Merle 1991). The first stage is at IP joint level; the next three stages are just distal, at or proximal (with intact thenar muscles) to MCP joint; in stage 5, the thenar muscles are lost; in stage 6, the first CMC joint is lost (scaphoid amputation) and the final stage is radio-carpal amputation. These three classifications take into account the important features of the thumb, namely thenar muscles and the first CMC joint. Strickland and Kleinmann divided the thumb into thirds, amputation of the middle third being between the IP joint and the neck of the metacarpal (Strickland and Kleinmann 1993). Agarwal et al. classified their thumb amputation population into zone 1 (distal to the IP joint), zone 2 (between the MCP and the IP joints) and zone 3 (between the MCP and the CMC joints) (Agarwal et al. 2010). Dec classified finger amputations into six categories: distal phalanx, DIP joint, middle phalanx, PIP joint, proximal phalanx, and the MCP joint (Dec 2006).

The first classification of ring avulsion injuries was presented in 1981 (Urbaniak et al. 1981), and further refined in 1984 (Nissenbaum 1984). Kay et al. proposed a more detailed classification taking into account possible associated skeletal injury (Kay et al. 1989).

Fingertip amputation classifications have traditionally been based on the anatomy of the nail (Elsahy 1977, Ishikawa et al. 1990) or the arterial distribution around the distal phalanx (Hirase 1997). In 2000 Evans and Bernedis introduced a classification that takes into account the defects of the pulp, nail and the bone (Evans and Bernedis 2000).

2.2.2 MC-hand

Michon and Dolich introduced the term Metacarpal hand in 1974 (Michon and Dolich 1974). They determined the condition as either a hand with complete loss of all the digits or a hand with at least partial thumb function spared (thumb without fingers).
In 1997 Wei et al. proposed a classification of MC-hand based on the level of amputation of the fingers and the functional status of the thumb (Figure 1, Wei et al. 1997a). It was designed to guide in planning of reconstructive procedures and to predict achievable outcome with the reconstruction. The classification has two main categories based on the status of the thumb. In type 1, the thumb function is adequate and in type 2, the thumb needs to be reconstructed as well.

In 2001 Vilkki introduced his classification for the no-finger hand (Figure 2, Vilkki 2001). It too was designed to guide in the planning of reconstruction of the deficient hand. In Level A (the basic hand) there are at least two functioning finger MCP joints left and the thumb amputation is no proximal than at distal MC level. For an MCP joint to be usable, at least 5 mm of the bone of the proximal phalanx is required for osteosynthesis with the transferred toe. Thumb amputation at distal metacarpal level most likely spares some thenar function and the first CMC joint. Especially, the ability to adduct the thumb is critical since it is a very important function and it is difficult to reconstruct with tendon transfers. Similarly, the condition of the first CMC
Joint affects the achievable function of the thumb reconstruction, since it is virtually impossible to reconstruct adequate first CMC joint function with any toe transfer. In the reconstruction of the basic hand, no MTP joints are included in the transferred toes making the reconstruction easier and achieved function better. Every effort should be taken to meet the requirements of the basic hand when treating mutilating hand injuries. Restoring skeletal length and functioning joints will prove valuable for later reconstruction. The Level B refers to true MC-hand with only the first MC left as a movable component. It can be further divided into B1 with adequate thenar function and B2 without. When assessing the thenar function, the AdP muscle is of special importance because it is the most difficult to reconstruct with tendon transfers. Level C is a transmetacarpal amputation with radiocarpal and distal radioulnar joint intact allowing pronation and supination of the forearm. Further, wrist flexion-extension motion enables tenodesis effect which can be used to ease synergistic grasp and release function. Level D is more proximal wrist or distal antebrachial level amputation. The Vilkki classification has been the basis according to which our patients were grouped and presented in the original articles forming this study.

Paavilainen et al. divided transmetacarpal amputations into transverse (all fingers), ulnar, and radial oblique based on the orientation of the injury (Paavilainen et al. 2007). This classification guides in the planning of the reconstruction.
2.2.3 More complex classifications

According to Hand Injury Severity Score (HISS), each digital ray should be separately examined for injury in four categories: integument, skeletal, motor and neural (Campbell and Kay 1996). After that, the received ISMN score of the particular ray is multiplied by a weighting factor assigned to that ray. In addition, points are given from injuries which cannot be assigned to a particular ray (e.g. motor branch of the median nerve). A “Tic-Tac-Toe” classification system for mutilating injuries divided the hand into nine anatomical regions and seven injury types (Weinzweig and Weinzweig 1997). Each injury type can be subdivided into soft tissue loss, bone loss, or a combined tissue loss. Further, the vascular integrity of the hand and digits should be recorded. At the end, each injury is described by type, subtype, vascular status and zone. Both the HISS and the “Tic-Tac-Toe” classification systems are detailed but rather cumbersome to use.

A classification of traction avulsion amputations of the upper limb based on location of the injury in relation to the musculotendinous unit emphasizes the muscle and its motor nerve as a functional unit (Chuang et al. 2001). It is useful in the forearm and arm level amputations.

2.3 The incidence of the traumatic amputations and replantations of the upper extremity and an estimation of the need for toe-to-hand transfers

2.3.1 The incidence of traumatic amputations of the upper extremity

An annual incidence of 1.9–3.4 serious amputations per 100 000 inhabitants was recorded in central Finland (Vilkki and Göransson 1982). Serious amputation was defined as one of the thumb through, or proximal to, the IP joint; at least two fingers through, or proximal to, PIP joints; hand or arm amputation. A single replantation center in southern Finland with a referral area of 1.5 million inhabitants reported an annual incidence of 1.5/100 000 of upper extremity amputation injuries (both total and subtotal) in adults based on hospital databases of diagnoses and operations (Lindfors and Raatikainen 2010). Fifty-nine percent of those were considered severe according to the criteria by Vilkki (Vilkki and Göransson 1982). The same center reported a 0.42/100 000 inhabitants annual incidence of upper extremity amputation injuries in children aged 16 or under (Lindfors and Marttila 2012). Nylander et al. using the same criteria as Vilkki and based on epidemiological statistics of the year 1979, estimated the annual incidence of serious amputations in Sweden to be 1.4/100 000 inhabitants (Nylander et al. 1984). In a single Swedish replantation center cohort study over a period
of nine years, the annual incidence of partial or total amputations reached 1.9/100 000 inhabitants (Atroshi and Rosberg 2001). Further, the annual incidence for amputations through, or proximal to, the wrist was 0.11/100 000 inhabitants. According to Swedish Hospital Discharge Register, a 5.21/100 000 inhabitants annual incidence of traumatic amputations of body extremities was noted (Asplund et al. 2009). Eighty percent of those (n=3368) occurred in the upper limb yielding an annual incidence 4.17/100 000 inhabitants. The Hospital Discharge Register expresses public inpatient care data. The first two studies from Sweden show quite similar rates (Nylander et al. 1984, Atroshi and Rosberg 2001). The incidence in the study by Asplund et al. is double compared to that of the previous ones, most likely because it uses a different data collection method which may include also minor amputations not considered for replantation (Asplund et.al. 2009).

2.3.2 The epidemiology of replantation surgery

The need for replantation surgery in Denmark was estimated to be 0.5–0.7/100 000 inhabitants annually (Kiil 1982) in patients over 16 years. In Finland, it was estimated that annually 1.9–3.4/100 000 inhabitants would need replantation, 0.2–0.6 of them with a major amputation (Vilkki and Göransson 1982). In the Lindfors and Raatikainen study, 168 replantations or revascularizations were performed in adults over a 58 month period yielding a 2.3/100 000 inhabitants annual incidence based on a population of 1.5 million (Lindfors and Raatikainen 2010). Further, they report a success rate of 68%. A similar success rate was reported from the same hospital already in 1984 and 1985 (Asko-Seljavaara et al. 1988).

In an epidemiological study of upper extremity replantation surgery in the United States using an inpatient database covering more than 90% of all US community hospital discharges and data accumulated from years 2001, 2004 and 2007, 9407 patients as having upper extremity amputations were identified (Friedrich et al. 2011). One thousand three hundred and sixty-one (14.5%) of those patients underwent a replantation surgery. Increasing age, payer status (self-pay or state issued insurance), being treated in a rural or a non-teaching hospital were all independent factors less likely to be associated with replantation.

There are many possible reasons explaining the different results in the estimated need for replantation surgery in a given population. The working environment plays an important role. That is, the level of industry using high powered machinery, the presence of and adherence to work security regulations, the use of trained personnel to mention a few of the aspects of work safety. The rules of supply and demand also determine the
need for replantation surgery. If we have good quality replantation service available, the knowledge of that will spread first to health care staff and then into the public. With increasing knowledge, those seeking medical attention after traumatic amputation will be sent to proper facilities for care. The structure of the health care system and the social security sets the need for replantation surgery. As shown in the Friedrich et al. study, the payer status affected the likelihood of replantation after an amputation (Friedrich et al. 2011). Further, the level of financial compensation during disablement may influence the decision of and hence the need for replantation surgery. Finally, cultural aspects influence the indications of replantation surgery. In certain Asian cultures, patients demand even the smallest parts of a single finger to be replanted.

2.3.3 An estimation of the need for post-traumatic grip reconstruction with a toe-to-hand transfer

There is no published data on the incidence for the microvascular toe-to-hand transfer operations in post-traumatic grip reconstructions. We can only estimate the need for such operations by looking at the current literature on the incidence of amputations and the success rates of replantations. The need for microvascular post-traumatic grip reconstruction derives from the incidence of traumatic amputations and the success of primary replantation service. The weakness of this reasoning is that not all patients whose replantations fail should be offered or are willing to consider a toe-to-hand transfer. Further, not all patients with a major traumatic amputation at the upper extremity will undergo replantation due to poor condition of the amputated body part or the patient.

In Finland, according to the Lindfors and Raatikainen study; there are annually 0.9/100 000 adult inhabitants who have serious upper extremity amputations of which 32% will fail replantation (Lindfors and Raatikainen 2010). Given the 5.4 million population of Finland (at the end of 2012 according to Population Register Centre), this leads to around 16 adult patients every year potentially in the need of microvascular post-traumatic grip reconstruction. For example, in Sweden, based on the Nylander et al. estimation of serious amputations (Nylander et al. 1982), population 9.5 million (at the end of 2012, Wikipedia) and a success rate of 70%, there are around 40 of these patients every year.
2.4 Indications and timing for post-traumatic microvascular toe transfers

2.4.1 Indications

The indications for post-traumatic microvascular toe-to-hand transfers can be evaluated by looking at scientific literature on the subject and then extracting the frequencies when a toe has been used to reconstruct different elements of the hand. This holds the premise that what we do reflects our indications. Another way to approach the issue of indication is to evaluate what the hand does what it needs to accomplish that. The title of this academic dissertation reveals our indications for post-traumatic toe-to-hand transfers, which fall into the latter approach: grip reconstruction.

The basic function of the hand is prehension, the ability to grasp and manipulate objects. Prehension can be described as “all the functions that are put into play when an object is grasped by the hands – intent, permanent sensory control, and mechanism of grip” (Tubiana et al. 1996).

The very elemental requirements for grip are two opposable digits of which at least the other should be capable of motion (Moran and Berger 2003). The other can function as post. A cleft or an opening is needed in between to accommodate an object. The two digits have to have adequate sensation and they must be free of pain. The TAROM of the two digits determines the width of the grip, and the strength exerted by the active muscle contraction determines the force the digits can direct to the object. Depending on the position and control of the two digits, precision pinch, oppositional pinch or key pinch are possible. This type of reconstruction is indicated when an amputation leaves the hand with no mobile digital elements. Probably the first reconstruction of this kind was performed by Oehlecker in 1919 with a pedicled transfer of great toe to the forearm (I). Then, two toes, one in index and one in thumb position, were transferred to reconstruct a post-traumatic MC-hand-type amputation (O’Brien et al. 1978a). Further, a method of transferring two second toes the end of the radius was described (Chen and Bao 1980). This technique was refined first by using a great toe (Furnas and Achauer 1983) and later by using a single second toe and attaching it to side of the radius (Vilkki 1985).

A more versatile grip is that of three digits forming a tripod pinch. In 1973, Tsai performed a combined transfer of second and third toes to reconstruct an ulnar post for the thumb in a case of transmetacarpal amputated hand (Tsai 1979). The same institute published later a case series of nine instances of combined transfers in eight patients (Tsai et al. 1981). In four of those patients, an innervated flap from the fibular side of the great toe (a hemipulp flap) was included to cover previously constructed osteoplastic thumb. In cases of bilateral MC-hand type amputations, the number of transplantable
Post-traumatic Grip Reconstruction with Toe Transfers

Post-traumatic grip becomes an issue. Pisarek introduced the first report of multiple toe transfers to reconstruct a bilateral MC-hand in 1990 (Pisarek 1990). In three different operations, he transferred three toes to both hands (six transferred toes in total) in a 31-year-old patient who had lost all ten digits in a frostbite injury. According to a systematic approach to the treatment of bilateral MC-hand (without a functioning thumb), three opposable digits should be reconstructed to the dominant hand and two to the non-dominant hand (Tan et al. 1999).

The two and three digit grip reconstructions indicated after severe amputations produce very basic hand function. With more intact mobile elements spared, a more sophisticated grip can be pursued. A hand requiring finger reconstruction is defined here as a hand with adequate thumb function (no need for reconstruction of thumb functions) and at least two functioning finger MCP joints. In the first toe-to-finger reconstruction, the second toe was transferred to index finger position in a 12-year-old patient with an amputation of index to ring fingers at the level of PIP joints (Ohmori and Harii 1975). A first simultaneous double second toe transfer to reconstruct adjacent long fingers just proximal to PIP joints was performed in 1977 (Ohtsuka et al. 1977). Since toes are shorter than fingers, the whole length of a finger cannot be reconstructed. Toe transfers are ideal in finger reconstruction beyond PIP joint level when some full length fingers are still present in the hand (Wei and Colony 1989). For more proximal amputations, especially when no fingers are spared, a double (second and third) toe transfer may be used. The first this kind of transfer was performed in 1978 to reconstruct a hand with amputation of all the fingers in a 27 year old patient (O’Brien et al. 1978a). In 1989 Wei et al. reported the results of 26 consecutive second and third toe composite block transfers and established indications for these types of transfers (Wei et al. 1989). According to them, reconstruction of adjacent absent fingers at or proximal to digital webs would be candidates for composite block transfers. Distal to this, composite block transfer would create a long palm – short finger appearing hand and, therefore, solitary toe transfers should be preferred. Due to the length limitation of the transferred toes, the pinch point and grasp arch fall short of that of normal length fingers. When salvaged fingers reach beyond the tip of the little finger, toe transfers will inherently be too short and contribute less to a fluent prehension.

The thumb plays a major role in the function of the hand. It contributes in almost all forms of grip. The significance of the thumb in prehension has been estimated to be as high as 40–50% (Strickland and Kleinmann 1993). Therefore, it was logical that the thumb was the first digit to be reconstructed (Dongyue and Yudong 1979). The first reconstruction was done with a second toe transfer in 1966 to a patient who had sustained a transtametacarpal amputation leaving the first CMC joint intact. Thumb amputations at or even proximal to the IP joint may cause minimal functional
impairment and can be tolerated well (Moran and Berger 2003). The level of thumb amputation benefiting from reconstruction is under debate. Some authors recommend thumb reconstruction when amputation is at the level of IP joint (Lee et al. 1995), through the proximal phalanx (Buncke and Buncke 2007), at or proximal to the middle of the proximal phalanx (O’Brien et al. 1978b), or at 1cm distal to MCP joint or proximal to it (Leung 1985). In cases where articular surface of the metacarpal head and sufficient capsular structures have survived, the MCP joint can be reconstructed by creating an articulation between the toe proximal phalanx and the metacarpal bone. This method of composite joint reconstruction was first described for congenital cases (Gilbert 1982) and later for post-traumatic cases (Poppen et al. 1983). In a recent systematic review presenting 450 toe-to-thumb reconstructions distal to MCP joint, great toe was used 196 (44%), wrap-around 122 (27%), second toe 101 (22%) and trimmed toe 31 (7%) times (Lin et al. 2011).

The above-mentioned indications for toe transfers all derive from the idea of reconstructing lost gripping ability. Therefore, the indication in them can be called functional. However, virtually all traumatized tissue components of a digit can be replaced with microvascular “like tissue” transfers from a toe. These include bone and tendons (Vitkus 1988), nail, glabrous (and other types of) skin, joints, and any combination of the aforementioned (Morrison et al. 1979). Microvascular partial toe transfers for cosmetic indications can produce good outcomes (Woo et al. 2006). Further along, this academic dissertation will focus on the microvascular toe transfers performed for functional indications since they fit under the title of this study.

2.4.2 Timing

The scientific literature concerning the timing of the post-traumatic toe-to-hand transfer is filled with confusing terminology. Terms like emergency, immediate, acute, primary, sub-acute, chronic, secondary and elective are not uniformly defined when used describing the timing of the reconstruction. Some authors include toe transfers performed within 2 weeks of the initial trauma under heading immediate (Woo 2004), while others are stricter and consider 24 hour limit for emergency toe transfers (Ninkovic 1995). Yim et al. defined toe-to-hand transplantation primary when it was done before a definite coverage of the initial wound and secondary when transplantation was done after the definite coverage (Yim et al. 2004).

Godina, describing a population of both upper and lower extremity trauma, divided the timing of the reconstruction into three categories: early (within 72 hours of the initial trauma), delayed (72h to 3 months) and late (more than 3 months) based on the healing status of the wound (Godina 1986). He found that the survival of the flap, infection rate, bone-healing time, duration of hospital stay and the number of operations were all in favor of earlier instead of later reconstruction. In a report of emergency free flaps performed for soft tissue coverage after debridement within 24 hours of the initial trauma, meticulousness of the debridement was emphasized (Lister and Scheker 1988). Surgically clean wound without any de-vital tissue and a stable skeleton were considered the prerequisites for an emergency free flap.

The advantage of primary toe-to-hand transplantation is earlier commencement of recovery and rehabilitation and therefore quicker progress to post-reconstructive state of function (Yim et al. 2004). Sometimes revision amputation inflicts further damage to important structures such as nerves, bone or tendons (Ray et al. 2009). Further, no fibrosis, scar adhesions or atrophy of tendons and muscles are complicating a primary reconstruction (Woo et al. 2004). Since the operation is technically demanding and time consuming, it poses a major challenge for the reconstructive surgical team and their organization. When injury is deemed unsuitable for primary reconstruction or when the patient is unsure about the toe-to-hand transfer operation, primary coverage is indicated. Only when a patient has lived with the defect for a while, can he or she estimate the need for toe-to-hand transfer (Yim et al. 2004). A delay of at least 6 to 8 weeks between the injury and the microvascular toe-transfer can be recommended in order for the patient to comprehend the functional loss caused by the injury, appreciate the possible gain of the reconstruction and psychologically prepare for operation and rehabilitation (Buncke and Buncke 2007).

2.5 Postoperative care and rehabilitation

2.5.1 Postoperative care

Immediate postoperative care of the recipient or the donor site after microvascular toe-to-hand transfer has not been a subject of a scientific study. On the contrary, authors report their postoperative protocols based on personal or institutional experience. In general, the goal of postoperative treatment is to avoid early complications such as vascular compromise and infection.

Most authors recommend using at least some sort of anticoagulation postoperatively. Dextran (low molecular weight) can be administered before completing the arterial
anastomosis and continuing with the medication 4 to 5 days postoperatively (Wei et al. 2003). Other anticoagulation therapy consists of varying doses and durations of acetylsalicylic acid (Patradul et al. 2000) and dipyridamole (Urbaniak 1985). Some use routinely anticoagulant and antiplatelet agents (Huang et al. 2011), some reserve them for take-back situations or when there has been an intraoperative vascular thrombotic event (Buncke et al. 2007), while some prefer not to use any anticoagulants, vasodilators or antiplatelet agents (Lister et al. 1983).

Prophylactic antibiotic therapy can be used routinely (Patradul et al. 2000) or in cases of prolonged surgical time or dirty wounds (Wei et al. 2003). Most authors, however, discourage using prophylactic antibiotics.

Postoperatively the operated hand and the foot are elevated to reduce edema and to control pain (Herrera et al. 2009). The hand can be placed in a splint at the end of the reconstructive operation (Urbaniak 1985) or a few days after the operation (Herrera et al. 2009). The hand is gently wrapped leaving the transferred toe visible for observation (Wei et al. 2003). The patient may be monitored in the intensive care unit for the first 48 hours (Buncke and Buncke 2007) or by specialized nurses (Wei et al. 2003). The vascular condition of the transplanted toe can be monitored by various methods. Most commonly used are observation of skin color, capillary refill and turgor and objectively by measuring skin temperature of the transferred toe and comparing it to other fingers of the operated hand or contralateral hand (Wei et al. 2003). Ultrasound Doppler can be used to assess artery patency when other methods yield inconclusive results.

### 2.5.2 Motor rehabilitation

Limited gentle active flexion-extension of the transplanted second toe can be started from second week onwards (Leung et al. 1981). Three weeks postoperatively the dressing from the hand is changed to an orthoplast splint, which maintains the wrist in extension. The splint is removed daily to allow wrist and finger exercises. An outrigger may be used to protect the weaker extension mechanism against stronger flexor tendons.

According to a rehabilitation program for patients who had had a great toe-to-thumb transfer, the reconstructed hand is placed in a plaster spica cast immediately after the operation (Robbins and Reece 1985). Edema control and gentle active mobilization (excluding great toe IP joint) is begun right away. Six to eight weeks after the transfer, the active isolated IP joint motion and abduction are allowed. Passive mobilization of the transferred toe is begun at seven weeks.

A five stage motor rehabilitation protocol introduced for patients with a microvascular toe transfer is adjusted individually to meet specific needs of the patient...
and prerequisites of the operation (Wei et al. 1992). Since second and third toe transfers have a tendency to claw, they are advised to be held in extension by a K-wire for the first two weeks and by an extension splinting thereafter. According to the protocol, the viability of the transferred toes is controlled during the first three days and the patient is provided with psychological support. After that and until week 4, gentle passive ROM exercises are gradually introduced starting from joints farthest away from bone fixation. The edema is controlled by elevation and a light-pressure tubigrip, which is applied at week 3. From week 5 onwards, gentle active exercises are started and scar management including more aggressive compression wrapping is commenced. Then, progressively, daily living (week 7 on) and vocational (week 8 on) activities are begun.

2.5.3 Sensory rehabilitation

Sensory rehabilitation aims at improving the interpretation of altered sensory input reaching the brain from peripheral nerves (Ma et al. 1996). To achieve that, higher cortical functions such as concentration, learning and memory are used. The early sensory rehabilitation, focusing on correctly localizing different modalities of touch, is begun when the patient can detect 30-cps vibration (from a tuning fork) with the transferred toe. This is because the ability to perceive a moving-touch stimulus was predicted earliest in the recovery process by the perception of 30-cps vibration (Dellon et al. 1972). The late-phase sensory rehabilitation, subsequent to recovery of moving and constant touch sensation, focuses on size, shape and texture discrimination (Wei and Ma 1995).

2.5.4 Donor site rehabilitation

The donor site rehabilitation has drawn little attention in the scientific literature. In the rehabilitation protocol presented by Wei et al. the donor site desensitization and gentle passive movements are begun already during the first three postoperative days (Wei et al. 1992). Gait training is begun at fourth week and donor site desensitization is increased at sixth week after the transfer operation.
2.6 Results of microvascular toe transfer operations

2.6.1 Survival

Survival of the transferred toe is an absolute prerequisite for achieving gain of the reconstructive operation. However, survival alone does not equate to success. In a 2011 published systematic review of the outcomes of toe-to-thumb transfers, a mean survival rate of 96.4% (range 80.8–100) was reported (Lin et al. 2011). The review could not detect differences in the rate of survival between different types of toe transfers (second toe, great toe, wrap-around or trimmed toe). As high as 26% (5/19) failure rate has been reported in patients with thumb or finger reconstruction with a wrap-around transfer (Lowdon et al. 1987). In the largest so far reported cohort of patients who had had a toe-to-hand transfer, 14 failed cases among 400 patients was noted, yielding a survival rate of 96.5% (Gu et al. 1997). Incorrect management of vascular variations (n=5), incorrect management of circulatory crisis (n=4), poor anastomotic technique (n=4) and high blood coagulation state (n=1) were found to be the causes of these failures (Gu et al. 1993). A single failure and a survival rate of 99.6% were reported in a retrospective personal series of 252 various (including vascularized toe joints) toe transfers (Lin 2013). Interestingly, an improvement over time could be noted in the survival rate (Gu et al. 1997, Kvernmo and Tsai 2011) and a decrease in the need for re-explorations (Lister et al. 1983, Kvernmo and Tsai 2011).

A 100% survival rate has been reported in patients with immediate toe-to-thumb reconstruction (Ray et al. 2009, Huang et al. 2011). In one study, the immediate cases survived better than elective cases (Woo et al. 2004), while in another, no marked difference in the survival rate could be stated (Yim et al. 2004). In conclusion, it seems that early reconstruction carries no additional risk of failure.

In a report of 26 combined second and third toe transfers, only one partial loss of the tip of the third toe was noted (Wei et al. 1989). A few years later, the same institute reported a series of four patients with 6 double second-third en block toe transfers, used for composite MCP joint reconstruction, all of which survived (Strauch et al. 1993). The reported survival rate of double second toe transfers varies between 96.5% (Herrera et al. 2009) to 99% (Coskunfirat et al. 2005). So, double second and third toes or simultaneous double second toe transfers seem to have the same survival rate as single toe transfers.
2.6.2 Recipient site results

2.6.2.1 Primary outcomes

The goal of a microvascular toe transfer is to augment the function of the traumatized hand. Consequently, tests that measure function, both patient-reported and clinician-based, can be considered as primary outcome measures. Reporting such results has not been common after toe transfer operations. It must be emphasized, that the results presented here are based on small retrospective patient series. This limits the generalization and increases the risk of chance influencing the results.

A pivotal study is that of Chung and Wei where they could show, in a mean of 7 y follow-up, that patients who had had a post-traumatic thumb reconstruction at MCP joint level with a toe transfer (a second or a great toe) (n=16) reported better function, work performance, aesthetics and satisfaction (according to MHQ) than those who refused the operation (n=5) (Chung and Wei 2000). Further, strength and dexterity of the toe transfer hands were comparable to contralateral control hands. Similarly, when comparing the functional results after thumb reconstruction (index pollicization n=3, osteocutaneous lateral arm flap n=4 and second toe transfer n=4) to nine patients with thumb amputation at the level of proximal phalanx, a statistically significant difference and a high effective improvement of hand function could be detected in favor of thumb reconstruction measured with a M2-DASH questionnaire (Parvizi et al. 2012). The second toe transfer was superior (mean M2 DASH 8.32 ±11.17) to osteocutaneous lateral arm flap (19.44 ±12.15) and pollicization (31.01 ±23.62). An improvement in all domains of the MHQ questionnaire, except pain level, could be shown in patients who had had thumb reconstruction with the second toe or the wrap-around flap when comparing pre- (based on patients’ recollection) and postoperative situation (Fan et al. 2006). Still, patients with a reconstructed thumb displayed difficulties in tasks requiring precision, such as buttoning up, winding a watch or picking up a pin (Frykman et al. 1986) and precision sensory grip or grasping small objects (Poppen et al. 1983). On the other hand, Doi et al. stated that pick-up testing, grasping and pinch power were satisfactory in six patients with wrap-around thumb reconstruction (Doi et al. 1985).

The extent of the thumb injury both proximally and towards the ulnar fingers has an effect on the reached function. That is, better outcomes were achieved with thumb reconstruction in patients with MCP joint or metacarpal level amputation compared to ones with CMC joint level (including thenar muscles) or radial hemi-hand (total loss of thumb with radial one or two fingers) amputation (Leung 1983). Similarly, patients with merely thumb amputation recovered better function compared to those with...
additional finger amputations when only the thumb was reconstructed (Poppen et al. 1983).

Primary outcomes for toe-to-finger reconstructions have not been published independently. Instead, these patients can be found in articles presenting thumb and finger reconstructions together. In a preliminary report of 12 patients with toe-to-hand transfer, it was noted that a second toe transfer, particularly replacing a finger, produces high satisfaction, even though the method of how satisfaction was measured or how many patients had finger reconstruction were not specified (Leung 1980a). In another report, it was stated that only one of eight toe-to-finger reconstructed patients had minor difficulties in manipulating small objects and that all the patients substantially improved in function after the reconstruction (Gordon et al. 1985). Similarly, good functional recovery was reported from three patients with toe-to-finger transfer (12 patients altogether) who could perform seven to 14 of the 16 required tasks in the functional testing (Frykman et al. 1986). Further, all of their patients found their hand more useful after the reconstruction.

Similarly to finger reconstruction, the results of MC-hand reconstructions are mostly from small patient series presented in conjunction with other types of reconstructions. Only two studies have measured function with tests in these patients. In the first, it was noted that 82.6% patients were independent in activities of daily living, overall function was assessed to be quite good, and Jebsen-Taylor showed below normal values with few exceptions in a cohort of seven patients (two of which were MC-hand amputees) reconstructed with multiple toe transfers (Williamson et al. 2001). In the second, two patients reported general satisfaction with the achieved function (according to MHQ scores) and received 10–20 seconds slower times with the reconstructed hand in the Jebsen-Taylor test when compared to contralateral uninjured hand (Chung and Kotsis 2002).

In the largest series describing the results of MC-hand reconstruction, it was stated that the hand function, although not specifically defined, was recovered in 59 out of 64 hands and opposition was nimble and forceful (Yu and Huang 2000). Further, their patients were satisfied and could use their hands in daily activities. In a report of six patients with bilateral metacarpal amputations, prehensile function had recovered enabling them to grasp, grip and pinch (Wei et al. 1999).

2.6.2.2 Secondary outcomes

Physical variables, such as range of motion, sensation and strength, all contribute to function but do not equate to it. That is, function of a reconstructed thumb or a finger
can be good even though range of motion, strength or sensation is not. Therefore, the outcomes of physical variables can be considered secondary.

According to an extensive literature search of post-traumatic toe-to-thumb reconstruction distal to MCP joint, the mean arc of motion of the transferred IP joint varies from 27° (trimmed toe) to 33° (great toe) and that of a total thumb ray (including MCP an IP joints) from 58° (great toe) to 110° (trimmed toe) (Lin et al. 2011). The mean arc of motion of the second toe transfer falls in between the two mentioned. The mean strength (reported as percentage of normal side) of grip varies from 69 (second toe) to 86 (wrap-around) and of key pinch from 50 (second toe) to 81 (great toe). The mean s2PD was between 10 and 11 mm. They could not find any statistically significant differences between the four transfer types used (second toe, great toe, wrap-around or trimmed toe) in the above mentioned physical variables. Further, they concluded that, for thumb reconstruction (n=51), great toe transfer yields best results (IP joint active ROM 31°, key pinch 3.3 kg) compared to trimmed great toe (ROM 13°, key pinch 2.1 kg) and to second toe (ROM 22°, key pinch 1.8 kg). They did not, however, provide greater detail on how the values were calculated or whether they were statistically significant. Huang et al. reports a mean s2PD of 7.6 ±1.2 mm, grip strength of 68 ±9.7% (of the contralateral intact hand) and high patient-reported (a score ranging from 1 (total thumb defect) to 100 (normal thumb)) satisfaction (mean 74.0 ±4.8) and function (mean 83.0 ±3.8) in eight patients with either emergency or immediate toe-to-thumb reconstruction (Huang et al. 2011).

For finger reconstruction, the second toe (single or double), independently or in combination with the third, are most commonly used. The reported mean active ROM of the transferred second (or third) toe IP joints (DIP and PIP combined) varies from 95° (Leung 1986) to 30° (Gordon 1985). An average 34.5° of extension lag in 55 second toe to finger transfers has been reported (Foucher and Moss 1991). The reported mean active ROM of the transferred MTP joint varies from 55° (Leung 1986) to 26° (Wei et al. 1988). The mean active ROM of the composite MCP joint was 52° in 11 reconstructed joints (Strauch et al. 1993). Further, Wei et al. reported a mean active ROM of 28° to 55° for the IP joints (depending on the level of amputation), 52.5° for the MTP joints and 59° for the composite MCP joints in children and adolescent population aged 3–16 (average 12) years (Wei et al. 1997b).

The achieved grip strength and pinching power are highly dependent on the extent of the injury in patients with toe-to-finger reconstruction. Normal grip strength and excellent pinching has been recorded after post-traumatic finger reconstruction with a toe transfer (Leung 1986). Others report a recovery of the grip strength to 50–67% (compared to the other side) and pinching power to 38–67 % (Foucher 1991, Herrera et al. 2009). Further, a 20.4 kg grip strength and 4.8 kg pulp-to-pulp pinch power
has been reported in seven patients with at least six (mean 22.8) months of follow-up (Gordon et al. 1985).

The results of motion and strength accomplished with toe transfers of MC-hand and AB-stump amputations are more modest than those previously presented. In a report of eight patients who had had multiple toe transfers to reconstruct a post-traumatic MC-hand, a mean active ROM of 22° at the MTP joint and 53° at IP joints was achieved (Tsai et al. 1981). Further, four of five patients who had had two to three toes transferred to reconstruct a hand with a post-traumatic metacarpal amputation averaged 3.5 kg (range 2–5kg) of grip strength (Del Piñal et al. 2007). Those four patients had an independent grip with a mean width of 9.6 cm.

The most widely used method to evaluate sensation in toe transfer patients is s2PD. Two-hundred sixteen (90%) of the 240 patients (with all types of toe transfers) tested recognized s2PD of <10mm (Gu et al. 1997). A mean 5.5 mm (range 3–12) s2PD (Leung 1986) to a mean 7.5 mm (range 3–13) s2PD (Coskunfirat et al. 2005) has been reported. Interestingly, a statistically significant correlation between better sensibility (mean 8 mm, measured with s2PD) and younger age (p<0.01), more proximal amputation (p<0.01) and a lack of compensation claim (p<0.05) could be shown (Foucher and Moss 1991). Their patient material consisted of 42 patients (55 transferred toes) of which nine were operated because of congenital anomalies and the rest were post-traumatic reconstructions. Further, length of the follow-up influenced the recovery of sensation, as in 16 patients with less than two year follow-up only 6 (37.5%) identified <10mm s2PD, while nine (75%) of 12 patients with over two year follow-up did so (Lister et al. 1983). In a more detailed evaluation of the recovery of sensory function, the sensation of the transplanted toe was compared to, and expressed relative to, that of corresponding contralateral normal finger and normal toe (Chu and Wei 1995). They found out, in a cohort of 21 patients who had had toe-to-hand transplantation after traumatic amputation that temperature sensation recovered nearly completely, with signs of hypersensitivity to cold, followed by the sensation of a pinprick. Recovery of sensation of vibration and touch reached 70% level compared to normal finger. The mean s2PD was 2.9 ±0.9 mm for the normal finger, 6.2 ±2.7 mm for the normal toe and 9.1 ±5.1 mm for the transplanted toe. They conclude that the sensory status of the transplanted toe resembled more that of a normal toe than a normal finger. The influence of the severity of the initial trauma to the recovery of sensation was demonstrated in a cohort of 30 patients with a post-traumatic toe-to-thumb or finger reconstructions (Leung 1989). That is, patients with more distal amputations (the non-fibrotic group) recovered faster and better than those with more proximal amputations (the fibrotic group). Formal sensory reeducation program seemed to enhance the recovery of sensation in both groups. Similarly, a sensory reeducation program started
13 to 98 (mean 33) months after the transfer operation induced a statistically significant mean improvement of 7 mm in s2PD and 6 mm in m2PD in 22 transplanted toes (Wei and Ma 1995).

2.6.3 Donor site results

To fully comprehend the results of toe-to-hand transfers, donor site consequences must be taken into account. It would seem reasonable that all the toes, especially the first and the second, have a function in the foot, and therefore removing them would cause dysfunction.

However, no statistically significant differences in mean LLFQ scores between patients who had had a toe transfer (12 great toes and four second toes) to reconstruct an amputated thumb and those (n=6) who had refused the operation could be detected (Chung and Wei 2000). Nor was there a difference between patients with great or second toe transfers.

Barca et al. compared the pre- and postoperative donor site results of four total great toe (including the MTP joint), 13 wrap-around, 27 modified wrap-around (including the distal phalanx of the toe), and 10 second toe (including MTP joint) transfers 2–144 months after the operation (Barca et al. 1995). They found out that each method of transfer had distinctive consequences: an overload of central and lateral metatarsals after the great toe transfer; lateralization of the center of pressure and hallux rigidus, decrease of great toe thrust (when FHL was harvested) and increase in the weight bearing pressure of the third metatarsal head after wrap-around transfer. They conclude that, since second toe transfer was not associated with functional or cosmetic changes, it should be preferred as a transplant.

Instead, in a prospective series of 12 patients who had had a great toe-to-thumb transfer, no significant change in the mean velocity, cadence, step length of the foot that where the toe was removed, single and double limb stance times or step width between pre- and postoperative gait analyses were detected (Lipton et al. 1987). Only two of their patients reported mild discomfort in the area of second and third MTP joints and one patient had intolerance to cold. Likewise, Poppen et al. found no alterations in the percent of stance phase; heel rise time or step length in gait analyses of ten patients examined a mean 42 months after great toe transfer (Poppen et al. 1983). However, a concentration of weight bearing between second and third metatarsals and on the lateral border of the foot on a pressure sensitive mat was noted. In addition, the center of pressure determinations revealed much slower forward and medial progression with prolonged weight bearing over the metatarsal heads concentrated on a smaller area of
the operated foot compared to the contralateral. Their patients rated the functional capacity, reported as a percentage value of the contralateral foot, to a mean 85% (range 50–97) and appearance to a mean 68% (range 30–95). Further, 23 (31%) of 73 patients with a great toe transfer reported suffering from cold weather aching and the return to prior activity level was estimated to be 95% (Lee and Buncke 2007).

Gait analysis failed to show differences between operated and control feet and pedoscope (fluoroscope) analysis discovered that most among 61 patients who had had a second toe transfer had developed flat foot (Yoshimura 1984). Gu et al. report that 91.6% of patients with a second toe transfer and 85.6% of patients with combined second and third toe transfers indicated good satisfaction in at least 2-year follow-up of a cohort 240 patients (Gu et al. 1997). Similarly, 86% of 84 patients with a second toe (with or without the MTP joint)-, multiple toe-, or second toe MTP joint transfers recovered completely normal foot function and were very satisfied in a mean 6.5 year (range 2 month–19 year) follow-up (Yang and Gu 2000). Most often occurring conditions, though mild and not interfering with work or normal activities, were numbness (n=13), pain on movement (n=6), cold intolerance (n=6), and callus (n=6). They found, however, 13 cases (15%) of deformities: five scissor-, four hallux valgus-, two fork deformities and two shortened toes.

Del Piñal et al. evaluated the donor site defect with a questionnaire and a reduced AOFAS scale in five patients who had had 2–3 toes transferred to reconstruct a MC-hand type amputation (Del Piñal et al. 2007). They report a mean 3 and 3.4 disability (on a scale 0–10, 0 = no limitation and 10 = disabling limitation) for fatigue on walking and difficulty to run, respectively. Further, the mean AOFAS score was 38 (out of 65), range 32–47.

In a report of 11 children (aged 6.5–12.1y) who had had 15 second toes removed 5 years earlier for digital reconstruction of anomalous hand, the gait kinematics were unaltered (Beyaert et al. 2003). However, anatomic anomalies (hallux valgus, claw toe and foot narrowing) and postural instability in stressful conditions (single-foot stance, eyes closed) were observed. Pain was exhibited in five and scar was judged hypertrophic in nine out of 15 feet. Contrary to the aforementioned study, Wei et al. found no difficulties of running or jumping or had any serious disturbances of foot function in a mean 3 years follow-up in 28 children, who at the age 3–16 years had had various toe transfers (Wei et al. 1997).
2.6.4 Radiological results

Radiological long-term effects, such as arthritis or osteopenia, of the recipient site have not been reported previously. Therefore, this chapter will focus on the donor site.

Eleven of the 15 patients who had had great toe-to-thumb transfers had signs of osteopenia (mostly mild) and stress hypertrophy of the second metatarsus next to the transferred great toe (Tiamfook et al. 1994). Further, the longitudinal and medial arch angle decreased in 12 patients, in eight patients the sesamoid bones had retracted proximally and dorsally, and the second MTP joint had assumed a varus alignment. Similarly, Mann et al. noted, in a cohort of ten patients who had had a great toe transfer evaluated with weight-bearing x-rays, a descent of medial longitudinal arch, a proximal migration of the sesamoid bones (mean 1.1 cm), a varus drift of the second MTP joint (mean 6°), and a plantar flexion of the first MT (Mann et al. 1988).

In a pediatric patient cohort, discussed earlier, an association with second toe transfer and forefoot anomalies, in particular HV and claw toe was noted (Beyaert et al. 2003). That is, seven (47%) of the 15 operated feet demonstrated HV in the weight-bearing x-ray, four of them overt (HV angle 20–26°) malalignment. Interestingly, the incidence of HV was also greater in the non-operated foot (28%) compared to general pediatric population (17%, according to Jerosch and Mamsch 1998).

2.6.5 Complications and secondary operations

In general, complications can be divided into local, either recipient or donor site, and systemic. The ultimate local complication of a toe transfer operation is the inability to achieve and maintain sufficient circulation of the transplanted part leading to necrosis. This subject is already covered in an earlier section (6.6.1 Survival). Secondary operations are typically performed months or years after initial reconstructive procedure to improve the function or appearance of the transplanted part or the donor site.

2.6.5.1 Recipient site complications

A significant early complication is a vascular compromise of the transplanted part necessitating re-exploration. The rate of re-explorations presented in the larger series of toe-to-hand transfers varies: 16.3% after 400 transfers (Gu et al. 1997), 9.3% after 140 double toe transfers (Coskunfirat et al. 2005), 18.6% after 113 transfers (Kvernmo and Tsai 2011) and 12.6% after 103 transfers (Wei et al. 1994). Leung describes a cohort of
25 patients, with a second toe transfer, of whom eight required one re-exploration and later five of them another re-exploration (Leung 1980b). This adds up to a total of 13 re-explorations in 25 patients. In a comparison of re-exploration rates between primary and secondary toe-to-hand transfers, an incidence of 9.7% (three cases) in primary and 11.7% (17 cases) in secondary reconstructions was found (Yim et al. 2004).

Wei et al. described 8 (5%) major postoperative infections requiring immediate additional reconstructive procedures in 121 patients with 152 transplants for distal digital reconstruction (Wei et al. 1993). Further, a superficial infection rate of 6.5% and 0.7% in primary and secondary reconstructions, respectively, has been reported (Yim et al. 2004). Other recipient site complications include two non-unions and one flexor tendon rupture during physical therapy in the 140 patients (Coskunfirat et al. 2005). In an ill-fated series of Lowdon et al, there were, in addition to the 5 (26%) failures, two patients with skin breakdown requiring trimming of the bone graft; one immediate infection requiring drainage; and one dorsal skin necrosis requiring groin flap coverage (Lowdon et al. 1987).

Bone graft resorbing, with an incidence of 50% (Lee et al. 1995), has been the problem with the wrap-around transfer. The level of reconstruction, the more proximal resulting more resorbing (Lee et al. 1995), and the length of follow up, 100% incidence when at least two year follow-up (Doi et al. 1985), seem to affect the rate of resorbing. The width of the bone graft, rather than the length, is more affected (Doi et al. 1985). Further, fatigue fractures have been described due to bone graft resorbing (Leung and Ma 1982, Lee et al. 1995).

2.6.5.2 Donor site complications

One case of a vascular compromise of a third toe, adjacent to a transferred second toe, leading to necrosis and loss of the toe has been described (Gordon et al. 1985). Despite the complication, the patient had no symptoms or problems with his gait. The most common donor site complication is, by far, delayed wound healing. In a systematic review of toe-to-thumb reconstructions, an incidence of delayed donor site wound healing of 4% in the second toe, 19% in the wrap-around, and 22% in the great toe transfers was recorded (Lin et al. 2011). They did not find any data with regards to complications after trimmed toe transfers. Yang and Gu found out that eight (9.5%) of their patients with a variety of transfers had delayed wound healing (>4 weeks) of the donor site (Yang and Gu 2000). One of those patients required a secondary operation to achieve healing of the donor wound. Further, Barca et al. reports no donor site complications in four great toe transfers, four (30.8%) cases of late wound healing
after wrap-around flap, six (22.2%) cases of non-specified complications after modified (inclusion of the distal phalanx of the great toe) wrap-around flap and one (10%) case of non-specified complication after second toe transfer (Barca et al. 1995). On the other hand, as low an incidence as only three cases (1%) of delayed wound healing among 280 second toes transferred has been reported (Coskunfirat et al. 2005).

2.6.5.3 Systemic complications

No studies reporting systemic complications after toe transfer operations were found.

2.6.5.4 Secondary operations

The indications for secondary operations after toe transfers vary considerably among reconstructive surgeons. Further, the willingness of patients to seek additional surgery to improve the function or the appearance of the transferred part or the donor site is a sum of psychological, cultural and functional desires. Hence, the actual rate of secondary operations reflects only partially the success of the original reconstructive procedure.

In the, so far, most comprehensive report of the secondary operations performed after a toe transfer, 14.3% (19 patients with 21 operations) of patients needed a secondary operation (Yim and Wei 1995). Of the transferred toes in that study, 13 were second toes (incidence of secondary operations=17.1%), 5 were combined second-third toes (16.1%), and one was great toe (5.9%). Further, of the 21 secondary operations, 12 targeted tendon (9 tenolysis), two were osteotomies, three were joint fusions, and four were soft tissue operations (3 web space deepenings). Other studies report the incidence of secondary operations as follows: 10% in a cohort of 73 great toe transfers (Lee and Buncke 2007), 65% in 54 toe transfers (Lister et al. 1983) and 70% in 277 second toe transfers (Coskunfirat et al. 2005). Most of the operations were performed to improve the scar, appearance of the transferred toe (pulp de-bulking), or the function of tendons. Pulp plasties were performed in nine toes (seven patients) in a cohort of 28 children who at the age 3–16 years had had in total 45 toes or toe tissues transferred (Wei et al. 1997). Contrary to adult patients, no tenolysis were needed. Two studies compared the need for secondary operations after primary and secondary toe transfers. The first reported an incidence of zero and 6 (4.2%), respectively (Yim et al. 2004) and the other 19 (76%) and 83 (128%), respectively (Woo et al. 2004) in favor of primary reconstructions. Despite the differences of the reported rates of secondary operations.
in the previous two studies, statistically significant difference was not reached (Yim et al. 2004) or calculated (Woo et al. 2004).

Studies reporting the rate of secondary operations, after toe transfers, performed on the donor site are far less frequent than on the recipient site. This is probably because the need for such procedures is rarer or they are of lesser interest. A minor scar revision in one patient and a correction of scissor deformity after a combined second and third toe transfer in another were performed in a cohort of patients who had had 46 toes transferred from 38 feet (Wei et al. 1988). Other secondary operations include six postoperative revisions (scar revision or skin graft procedure) after 20 toe transfers (Frykman et al. 1986) and one removal an osteophyte after 12 great toe transfers (Lipton et al. 1987).

2.7 Limitations of the literature

There were 134 articles included in this literature review. Ninety of those report techniques, outcomes or protocols related to microvascular toe transfers. Table 1 displays these articles according to the year of publication. After the innovation of microvascular toe transfer in the late 60’s, a clear increase of publications can be seen in the 80’s. New techniques presented as case reports turned into larger cohorts of patients. They were then further specified according to the target of reconstruction (thumb, finger etc.) and the transfer used (great toe, second toe etc.). Subsequently, studies presenting long-term follow-up of mainly secondary outcomes and donor site consequences emerged. Still, up to recent years a great number of publications offer technical refinements to existing procedures or describe bizarre amputations reconstructed in imaginative combinations of transferred tissues. There are, however, apparent shortcomings in the scientific literature concerning microvascular toe transfers.

Extensive literature search could produce only two studies which had a control group (Chung and Wei 2000, Parvizi et al. 2012). In both, the control group had an obvious selection bias since it consisted of patients who had refused reconstruction. Further, two studies which measured an outcome before and after an intervention (Barca et al. 1995 and Lipton et al. 1987), and one systematic review (Lin et al. 2011) were found. Despite rigorous exclusion criteria (isolate complete thumb amputation between MCP and IP (both excluded) joints), they could not find statistically significant differences in survival or secondary outcomes between different transfers used. Patient satisfaction was assessed in only 13% of transfers included in their study. Moreover, since donor site consequences were inadequately reported, no evidence-based recommendations...
could be made regarding which method of reconstruction is best suited for this strictly defined clinical situation.

The outcome measures of the recipient site concentrate on physical variables, such as motion, strength and sensation, which are often referred to as functional. Only two standardized questionnaires measuring ADL, the MHQ (Chung and Wei 2000, Fan et al. 2006) and the M2-DASH (Parvizi et al. 2012), and a single dexterity test, the Jebsen-Taylor test of Hand Function (Williamson et al. 2001, Chung and Kotsis 2002) have been used to evaluate recipient site outcomes in these patients. Further, one study (Chung and Wei 2000) has used a standardized questionnaire, the LLFQ, to evaluate the donor site outcome. No clinimetric data is available about these tests used in this patient population.

There are certain institutes that dominate the scientific field of toe transfers. By far, the most industrious is a group from Chang Gung Memorial Hospital in Taiwan under the leadership of Professor F-C Wei with 18 articles referred to in this literature review. Other productive clinics are the Chinese University of Hong Kong, China (Professor PC Leung) with eight articles; St. Vincent’s Hospital in Melbourne Australia (Director B O’Brien) six articles; Davies Medical Center/The Buncke Clinic in San Francisco United States (Dr. HJ Buncke) five articles; Kleinert institute/University of Louisville United States (Dr. T-M Tsai) five articles; and Hua-Shan hospital, Shanghai China (Professor Y Gu) four articles. There is an evident risk of reporting the results of same patients in multiple publications.

Table 1. The distribution of articles included in this academic dissertation according to the year of publication (n=90)*

<table>
<thead>
<tr>
<th>Years</th>
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</tr>
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<tr>
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<td>11–13</td>
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</table>

* Ninety articles included in the literature review which report techniques, outcomes or protocols related to microvascular toe transfers.
3 AIMS OF THE STUDY

The present study was undertaken in order to:

1) evaluate the long-term patient-reported and clinician-based outcomes of post-traumatic grip reconstruction using toe transfers in different patient populations:
   - AB-stump reconstruction (I)
   - MC-hand reconstruction (II)
   - Thumb reconstruction (III)
   - Finger reconstruction (IV)

2) report complications and secondary operations in these patients (I–V)

3) evaluate the influence that the extent and method of the injury has on the outcome (I–IV)

4) evaluate the long-term consequences that a toe-transfer has on the donor site (V)

5) evaluate whether the donor site defect is overcome by the recipient site gain after toe transfer operation (I–V)
4 PATIENTS AND METHODS

4.1 Patients

The patient population of this study is based on a personal series of one of the supervisors of this academic dissertation. The inclusion criterion for this study was traumatic amputation of a hand, or a part of it, necessitating a microvascular toe transfer to regain gripping ability. In this and the last paragraph under the topic Patients, the entire patient population is described. Otherwise, only those patients taking part in the clinical follow-up study are discussed. A total of 97 patients fulfilling the inclusion criterion were identified. These patients had had 98 hands reconstructed with 108 toes in 101 operations. The toes were taken from 102 feet. In addition, one hand of a patient who had had a single toe transferred from both feet to reconstruct a bilateral congenital absence of the hand (acheiria) was included in this study. This patient/hand was counted in because his case concurs with the method of AB-stump reconstruction for traumatic amputations. Of the 98 eligible patients, seven had died, due to unrelated reasons, after the operation and prior to the start of the study, and 11 could not be reached. For the rest, a letter containing an informed consent form was sent. Six patients did not want to participate. This yields a population of 74 patients (75 hands, 80 feet, 85 transferred toes in 79 procedures) participating in this study. Therefore, the response rate was 76%. One patient with bilateral amputation had thumb reconstruction on one side and AB-stump reconstruction on the other. The last two columns of Table 2 summarize the demographics of both the participants and drop-outs. The two groups are very similar in terms of age at injury, delay from injury to reconstruction, type of amputation, and the injury setting.

The patients were divided into four groups (thumb, finger, MC-hand, and AB-stump) based on the level of amputation and the need for targeted reconstruction to restore gripping ability according to the classification of no-finger hand by Vilkki (Vilkki 2001). The patients in the aforementioned groups were further divided into more specific subgroups to describe the injury in more detail. That is, thumb reconstruction patients were divided into four groups according to the level of amputation: group 1 = proximal phalanx; 2 = metacarpal with functioning thenar muscles; 3 = metacarpal
without functioning thenar muscles; and 4 = proximal to the first CMC joint. Next, finger reconstruction patients were divided into two groups based on whether the patient had any functional fingers left. Finally, AB-stump reconstruction patients were divided into three groups based on the level of amputation and remaining function of the wrist joint: motion at radio-carpal joint; motion at DRU joint; and proximal to DRU joint. Patients with this level amputation had sustained severe concomitant injuries. That is, two patients had lost their vision and four patients had substantial amputations in the contra-lateral hand. Pre-operatively none of the patients in the MC-hand or the AB-stump groups had prehension in the injured hand. Patient demographics and the details about the injury of each group are presented in Table 2.

The annual number of reconstructions is illustrated in Table 3. A slight decrease in the number of reconstructions can be detected from the high season of mid 80’ towards the end of the study period. This is probably due to improved replantation service established in the two major hand- and microsurgical units in Tampere and Helsinki.
Table 2. Patient demographics and details about the injury

<table>
<thead>
<tr>
<th></th>
<th>Finger</th>
<th>Thumb(^1)</th>
<th>MC-hand</th>
<th>AB-stump(^2)</th>
<th>Total (participants)(^3)(^,)(^4)</th>
<th>Drop-outs</th>
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</thead>
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<td>8/3</td>
<td>58/16</td>
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<tr>
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<td>[17–60]</td>
<td>[16–49]</td>
<td>[2–60]</td>
<td>[2–49]</td>
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<td>[30–65]</td>
<td>[19–70]</td>
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<td>[3–162]</td>
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<td>Follow-up (months)</td>
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<td>11</td>
<td>1</td>
</tr>
</tbody>
</table>

xx = not recorded in the patient files; n/a = not applicable
\(^1\) One patient suffered bilateral amputation in an explosion injury. One of his hands required a thumb and the other an antebrachial stump reconstruction.
\(^2\) One patient in the AB-stump reconstruction group was operated on because of a congenital apheria.
\(^3\) For the Vilkki classification, see Figure 2 and third paragraph under heading 2.2.2 MC-hand for clarification.
4.2 Methods

4.2.1 General considerations for lesser toe transfers (n=68 toes)

The lesser toes (second, third, fourth and fifth), when transferred to hand, have an inherent tendency to claw. In an effort to overcome this, the following adjustments to the second (or third) toe transfer were made:

1) The second (or third) toe has an intrinsic tendon-muscle mechanism resembling that of a finger. In theory, activating these intrinsic mechanisms would enhance the flexion of the MTP joint and extension of the IP joints as well as increasing the lateral stability of the transfer MTP joint. This modification was done in 34 single second (or third), one great, and four double second-third en block transfers. The intrinsic tendon reconstruction was done to 25 of the 27 transfers that were equipped with the MTP joint.

2) The FDS tendon, acting on the PIP joint, delivers better thumb-like flexion since the combined length of the toe distal and intermediate phalanxes approximates that of the thumb distal phalanx. The FDP tendon was tenodesed to the FDS (to prevent hyperextension of the DIP joint) which then was motorized during reconstruction. This modification was done in 21 cases where the transfer was placed in thumb position.

3) The short and the long extensors of the toe were separated from each other and motorized individually during reconstruction. The short extensor was tightened
4.2.2 Thumb reconstruction (n=41 patients)

The great toe was used in five and a third toe in one reconstruction. For the rest (n=35), a second toe was used. The second MTP joint was included in the transfer in eight patients. The average number of tendon reconstructions for patients who had MTP joint included in the transfer was 5.3 and for those without the joint 3.1. Inclusion of the MTP joint increases the reach of the transfer and therefore enables thumb reconstruction proximal to the MCP joint. A veno-subcutaneous flap from the dorsum of the second ray, as described by Vilkki (Vilkki 1995), was frequently harvested with the second toe transfer. It is used to cover dorsal tendon and bone connections of the recipient site with a well vascularized gliding surface. The transfer was equipped with 1–2 dorsal, in addition to volar, nerves in 93% (n=38) of cases.

4.2.3 Finger reconstruction (n=15 patients)

Finger reconstruction was done with a single second toe in nine patients. The double second-third en block transfer was used in four patients. Further, two second toes were transferred in a single operation to one patient and in two separate operations to one patient. In total, 21 toes were transferred from 17 feet in 16 operations to 15 patients. One MTP joint, as a part of double en block transfer, was included in the transfer in one patient for the reconstruction of the shorter of the two adjacent amputated fingers. Direct wound closure was possible in only two patients. For the rest, a STSG or a hemi-pulp flap from the great toe was needed. The double en block transfer was left in syndactyly for the first month to save the normal finger web. It was thereafter released enabling independent movement of the transferred toes. In seven (54%) of the single second toe transfers, 1–2 dorsal nerves, in addition to volar, were reconstructed.
4.2.4 MC-hand reconstruction (n=8 patients)

A single second toe, used in six patients, was placed in thumb position in five patients and it was always positioned to enable a simple pinch grip. One patient received two second toes in two separate operations and one patient had first double en block second-third toes transferred to finger position and in another operation a single second toe transferred to thumb position. In total, 11 toes were transferred from 10 feet in 10 operations to 8 patients. The intrinsic tendons were reconstructed in all the toes which were transferred with the MTP joint (n=9). One to two dorsal nerves, in addition to volar, were reconstructed in six of the transferred toes. A STSG was needed in all the operations, and an additional hemipulp flap from the great toe was used in two operations to cover the recipient site wound.

4.2.5 AB-stump reconstruction (n=11 patients)

The antebrachial stump amputation was reconstructed with either a single second (n=10) or a single fourth (n=1) toe. One transfer was positioned on the volar side of the radius because the patient was able to flex and extend the wrist joint. The rest of the transfers were attached to the radial side of the radius. All the transfers were harvested with the MTP joint and intrinsic tendons were always reconstructed. A hemipulp flap from the great toe was included in the transfer in ten cases. Both volar and dorsal nerves were reconstructed in every case.

4.2.6 The donor site (n=80 feet)

There were three different methods of toe harvest. Firstly, the great toe was used in five patients. The level of resection was at proximal phalanx in two, MTP joint in two and MT bone in one. The donor wound closure required a STSG in all cases. Secondly, a single second toe was used with the MTP joint included in the transfer in 25 patients (27 feet), and without the MTP joint in 38 patients (40 feet). A similar method of toe harvesting was used in patients with either a single third or a single fourth toe transfers. In 19 feet, a hemipulp flap from the fibular side of the great toe was included with the second toe transfer. The donor wound closure required a STSG in seven cases. Thirdly, a double en block transfer of second and third toes was harvested from five patients/feet. The donor skin was closed directly in four and with the help of a STSG in one patient.
4.2.7 Postoperative care and rehabilitation

After the operation the hand and the foot were held elevated. Postoperative monitoring with measuring skin temperature and evaluating vitality was done at hourly intervals during the first two to three days and thereafter less frequently. Prophylactic antibiotics were used in most cases. Rehabilitation was planned individually for each patient. Gentle active exercises were started one week after the operation under the supervision of a therapist. An individual dynamic extension splint was fabricated and worn from second week to 1–3 months. Typically, the IP joints of the transfer were supported towards extension and, when included, the MTP joints towards flexion. The donor foot was placed in walking plaster cast for the first month. Weight bearing was allowed and encouraged one week after the operation.

4.2.8 Study protocol

This was a retrospective cohort study. Patient charts were carefully evaluated and information about the initial amputation, reconstructive operation and postoperative period were recorded. Complications and secondary operations were determined from the patient charts and by asking the patient during the follow-up visit. Otherwise, the follow-up visit consisted of a radiographic and clinical evaluation of the recipient and the donor site. The outcomes of the study were divided into primary (function) and secondary (physical variables, satisfaction etc.). Further, the methods of reaching these outcomes were divided into patient-reported (questionnaires), clinician-based (tests) and radiographic. All the patients were examined by the author of this academic dissertation who had not taken part in the care of the patients.

4.2.8.1 Primary outcome methods

Two questionnaires were used. The first, which was sent to patients, was modified from the one proposed by the IFSSH subcommittee on replantation (Tamai et al. 1983). The questionnaire was translated to Finnish, the ADL section was modified to give the patients a six grade (instead of three grades) option for each question and questions concerning the replant were converted to questions about the toe transfer. Each of the 20 questions was answered according to preset options: easy, quite easy, quite difficult, difficult, impossible and I don’t know. This produced a scale ranging from 0 to 20 points. Managing the ADL quite easily corresponded to a result of ≥12.5 points.
The questionnaire formed a part of a score that was otherwise comprised of clinical examination of the hand. The questionnaire and the score are later referred as the modified Tamai questionnaire/ADL and the modified Tamai score. This questionnaire/score was chosen because our patient population approximately resembles that of the original publication.

A second questionnaire, designed by the author specifically for the toe transfer patients, was filled up during the clinical follow-up visit. This questionnaire consisted of questions about pain, sensibility, satisfaction, social acceptance, cosmetics and ADL (later referred as our hand ADL). The questionnaire for the thumb and finger reconstruction patients had 20 questions, 12 of which comprised the ADL section. A question concerning a hook grip was not asked from MC-hand and AB-stump reconstruction patients, since it is not possible even after the toe transfer. Therefore, their questionnaire had 19 questions, 11 of which comprised the ADL section. The questions were either generalized (e.g. handling oneself dressing up or washing up) or task and hand-oriented (e.g. strong gripping, handling coins, key pinch). Patients were asked to rate their answers into four categories, according to the level of complaint, equaled one (major complaint) to four (no complaint) points. A score ranging from 12 to 48 points (for thumb and finger reconstruction patients) or 11 to 44 points (for MC-hand and AB-stump reconstruction patients) was calculated from the ADL section of the questionnaire. At least 30 (thumb and finger) or 28 (MC-hand and AB-stump) points were needed for no or minor complaint in managing the ADL. The more points, the better the result, a feature shared by all the tests and questionnaires used in this study.

The SHFT, which is a dexterity test that has 20 tasks measuring different forms of grip (Sollerman and Ejeskär 1995), was used to evaluate our patients. Most of the tasks were completed single handed and, when both hands are needed, the other hand had a clearly defined assistant role. Both hands were tested. Each task was judged according to the following scale of performance: without difficulties (within 20 seconds); with slight difficulties (within 40 seconds); with great difficulties (within 60 seconds); incomplete completion (within 60 seconds); and not able to perform at all. This way, both the time and the quality of performance were judged. Points were given from 0 to 4 for each task so the total score varies between 0 and 80. Normal dominant hand should score 80 points and non-dominant hand 78–80 points. Passing the test with less than or equal to slight difficulties required 50 points.

Additionally, a modified Tamai score which is a combination of a questionnaire, as mentioned before, and a clinical examination, was used in our patients (Tamai et al. 1983). It has been originally designed to evaluate the hand function after a finger or a thumb replantation. Movement of the transfer in thumb position is judged on both
total active ROM and opposition, while only the former is assessed when the transfer is in finger position. Sensibility is evaluated according to the criteria set by the British Medical Research Council (Zachary 1954). As a part of the score, the patients were asked to rate their satisfaction of the final result of the reconstruction according to the following scale: 0 = not satisfied and would not, in retrospect, want the procedure done; 5 = not satisfied but would still, in retrospect, want the operation done; 10 = satisfied; 15 = fairly satisfied; 20 = highly satisfied. The score has range from -10 to 100 since 10 points can be deducted in case of inability to work because of the injury. A limit between good and fair result was set at 60 points. The Tamai score was reported from patients with MC-hand reconstruction when there was one transfer placed on thumb position (n=5). Further, only the total active ROM of the transfer was judged for patients with AB-stump reconstruction since opposition was not even intended, nor possible, with the method of reconstruction used.

Originally reported for finger reconstruction patients (IV), a new variable called Combined Score was calculated. The Combined Score was determined by adding up the results of the three individual primary outcome measures (our hand ADL, the SHFT and modified Tamai score). It provides a much wider perspective to evaluating function. A limit for good results was set at ≥ 172 points, which could be reached by scoring no complaint (≥ 42) in our hand ADL; no more than slight difficulties (≥ 50) in the SHFT; and an excellent result (≥ 80) in the modified Tamai score.

The primary outcomes of the donor site were evaluated with a questionnaire, designed by the author for microvascular toe transfer patients, and with an AOFAS scale (Kitaoka et al. 1994). The ADL section of the questionnaire (later referred as our foot ADL) had seven questions focusing on the function of the donor site. Similar to the recipient site questionnaire, the patients were asked to rate their answers into four categories according to the level of complaint yielding 1 to 4 points for each item. A score ranging from 7 to 28 points was calculated from the answers and a limit between moderate and minor complaint was set at 17.5 points. The AOFAS scale for hallux metatarsophalangeal-interphalangeal disorders consists of a questionnaire and a clinical examination of the foot. It was chosen because problems of this area, especially hallux valgus deformity, were expected after removal of a toe or toes. The AOFAS scale was inestimable from patients with a great toe transfer. The scale is divided into pain (40 points), function (45 points), and alignment (15 points). It has a range of 0 to 100 but does not translate the received score into a verbal category. For the purposes of this study, a limit to good result was set at 78 points. This could be reached when there was at most mild, occasional pain; no limitations of daily or recreational activities; no footwear limitations; only moderate restriction of the first MTP joint motion; full
range of the IP joint motion; no MTP–IP joint instability; no symptomatic callus; and at least fair alignment of the hallux.

4.2.8.2 Secondary outcome methods

Secondary patient-reported outcomes were included in both of our questionnaires (one for the recipient and one for the donor site). These items addressed pain, neuropathic symptoms, the outlook, general satisfaction of the outcome, and social acceptance. Similar to our ADL questionnaires, the patients rated their answers into four categories. Further, satisfaction with the cosmetic appearance of the transferred toe was evaluated with a VAS (0 = totally dissatisfied and 100 = totally satisfied) and expressed as a percentage.

Strength, sensibility and movement were measured as secondary clinician-based outcomes. Strength was measured as key pinch (between the two surfaces the patient used for key pinch) and grip strength. The registered value was the better of the two consecutive attempts. Sensibility was measured with Semmes-Weinstein filaments, both s2PD and m2PD, and as a distinction between a sharp and a dull touch. Since 2PD is difficult to measure reliably and reproducibly, specific values were not reported but rather a distinction between ≤10 mm and >10 mm was made. Sensibility was measured from the pulp of each transferred toe and its counterpart in the contralateral hand. Movement was measured with a goniometer. Since the lesser toes have short distal and intermediate phalanges making reliable measurement of movement between them difficult, the DIP and the PIP joints of the transfer were considered as one IP joint. Thus, the reported value of movement was between the distal and the proximal phalanges of these toes. The first web opening was measured and reported as millimeters and a cylinder grip width was evaluated with the ability grasp as large a diameter of cylinder as possible (1 cm increment increase in cylinder diameter starting from 6 cm). In order to assess how well the transfer approximates to the opposing surface, patients with MC-hand- or AB-stump reconstruction were asked to hold a sheet of A4 paper against gravity. In addition, the reach (towards the base of the fifth finger) and fluency of opposition of the transfer in thumb position were evaluated. All the measurements of physical variables were obtained from the other hand as well. Thus, the other hand acted as a control for patients with a unilateral injury. In addition to the clinical examination required for AOFAS scale, the donor foot was evaluated for restriction of operation scar, ability to stand up on tiptoes and stability of the first MT. Further, the first ray alignment was assessed, with the patient standing, and graded: normal (hallux
well aligned), fair (some degree of hallux malalignment, slight mallet toe deformity), and poor (obvious hallux malalignment, manifest mallet toe deformity).

4.2.8.3 Radiological outcome measures

During follow-up visit, radiographs were taken of hands, all the transfers and their counterparts in the other, uninjured hand. Further, both feet were radiographed with the patient standing up. The radiographs were assessed for any signs of osteoarthritis on a four grade scale (Gahunia et al. 1995) and osteopenia on a three grade scale (no, mild, marked). From the feet, the HVA, the IMA between the first and the second (IMA I–II) and the first and the third (IMA I–III) rays, and the width of the forefoot were measured. The radiographic classifying of the state of the hallux valgus deformity was determined as follows: normal (HVA <15°, IMA I–II <9°), mild (HVA 15–19°, IMA I–II 9–11°), moderate (HVA 20–40°, IMA I–II 12–15°) and severe (HVA >40°, IMA II–I ≥16°) (Coughlin 1996). All the radiographs were assessed by a radiologist not related to care of the patients.

4.2.9 Analyses of the data

Categorical variables were reported as frequencies and percentages, and tested with the Fisher’s exact test. Due to skewed distributions, continuous variables were expressed as medians and ranges and tested by the Mann-Whitney non-parametric test. Spearman’s correlation (r) was used to test the associations between primary outcome measures of the recipient and the donor site and physical variables and primary outcomes of the recipient site in thumb reconstruction patients. The closer the r-value was to +/- one, the greater the correlation was considered. Independent samples Kruskal-Wallis test was used to determine the association between the first ray alignment and the functional tests of the feet. Logistic regression models with odds ratios and 95% confidence intervals were used to examine the association between age, gender, the transfer used, number of nerves reconstructed, whether the MTP joint was included in the transfer or not, and the injury patterns with the following: the SHFT score <70 (≥70 means performing without difficulties); the modified Tamai score <60 (≥ 60 means good or excellent result); the modified Tamai ADL <12.5 (≥ 12.5 means easy or quite easy); our hand ADL <30 (≥ 30 means no or minor complaint); and with return to work. P values <0.05 were considered as statistically significant.
5 RESULTS

The median and (range) of follow-up of the 74 patients was 16 years 7 months (31–358 months) and for the 80 feet 16 years 4 months (11–358 months).

5.1 Survival

In total three toes were lost. Among the study population, there was a failure of one of the toes of a double second-third en block transfer. This yields a survival rate of 98.8% for the transferred toes attending this study. Considering the entire patient population (109 toes), there were two additional failures producing a survival rate of 97.2%.

5.2 Primary outcomes

The median (and range) values of the primary outcomes are presented in Table 4. In the following, the hand outcomes are discussed in more detail dividing the patient population according to the targeted reconstruction. Instead, the foot outcomes are presented from the whole patient group. There was a significant positive correlation between the AOFAS scale and the modified Tamai score ($r=0.414$, $p=0.002$). Similarly, our hand and foot ADL scores correlated positively with each other ($r=0.305$, $p=0.008$).

5.2.1 Thumb reconstruction patients

The tests used to measure primary outcomes (modified Tamai ADL, our hand ADL, the SHFT, and the modified Tamai score) had a positive correlation with each other ($r>0.4$, $p<0.05$).

Eleven of the 20 activities included in the modified Tamai ADL were considered on average easy or quite easy. Tasks requiring fine manipulation, like picking up a needle or a coin; using a safety pin; or buttoning up, posed most difficulties. Twenty-five patients could manage the ADL easily or quite easily and the rest had at least some difficulties.
## Table 4. Primary outcome measures

<table>
<thead>
<tr>
<th></th>
<th>Thumb</th>
<th>Finger</th>
<th>MC-hand</th>
<th>AB-stump</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No-finger hand</td>
<td>Some fingers left</td>
<td>Total</td>
<td>N (patients)</td>
<td></td>
</tr>
<tr>
<td>Modified Tamai ADL (0–20)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>75</td>
</tr>
<tr>
<td>Easy or quite easy / quite difficult or worse (n)</td>
<td>25/16</td>
<td>7/0</td>
<td>8/7</td>
<td>0/8</td>
<td>2/9</td>
</tr>
<tr>
<td>Our hand ADL²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No or minor / moderate or major complaint (n)</td>
<td>36/5</td>
<td>6/2</td>
<td>13/2</td>
<td>2/6</td>
<td>4/7</td>
</tr>
<tr>
<td>Sollerman (0–80)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Without or slight / great difficulties or worse (n)</td>
<td>40/1</td>
<td>8/0</td>
<td>7/0</td>
<td>5/3</td>
<td>3/8</td>
</tr>
<tr>
<td>Modified Tamai score (10–100)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excellent or good / fair or poor (n)</td>
<td>33/7</td>
<td>5/3</td>
<td>7/0</td>
<td>12/3</td>
<td>3/2</td>
</tr>
<tr>
<td>Combined score³</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Good / fair (n)</td>
<td>29/11</td>
<td>3/5</td>
<td>19/5</td>
<td>1/10</td>
<td>4/31</td>
</tr>
<tr>
<td>Our foot ADL (7–28)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No or minor / moderate or major complaint (n)</td>
<td>39/1</td>
<td>7/3</td>
<td>14/3</td>
<td>9/1</td>
<td>74/6</td>
</tr>
<tr>
<td>AOFAS scale (0–100)⁴</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Good / fair (n)</td>
<td>31/5</td>
<td>6/4</td>
<td>7/0</td>
<td>13/4</td>
<td>8/2</td>
</tr>
</tbody>
</table>

Note: n/a = not applicable

1 Finger reconstruction patients are divided based on whether any finger function was spared by the initial amputation.
2 Our hand ADL had 12 questions (range 12–48) for thumb and finger patients and 11 questions (range 11–44) for MC-hand and AB-stump patients.
3 Combined score is the sum of results of Our hand ADL, the Sollerman hand function test and the modified Tamai score.
4 The AOFAS scale was immeasurable from patients with a great toe transfer.
Similarly, handling small objects posed a moderate complaint according to our hand ADL. The rest of the tasks were considered at most a minor complaint.

The 20 tasks evaluated in the SHFT were generally performed without difficulties. Only using a screwdriver, turning hexagonal nuts and buttoning up were rated on average <3.5 points indicating that they were executed with slight difficulties. Furthermore, 36 (88%) patients performed the entire test without difficulties (score >70 points). According to the modified Tamai score, 34 (83%) of the patients received a good or excellent result.

Some of the associations that might explain differences in the primary outcomes are presented in Table 5. Patients with only thumbs amputated (n=18) scored better in the modified Tamai ADL compared to those with multiple rays amputated (n=23) (mean score 16 vs. 12, respectively (odds ratio 11.7, CI 2.24–63.6)). Also, patients with intact MCP joint or thenar muscles scored better than more proximally amputated patients in our hand ADL (65% no complaint vs. 0%, respectively), in the SHFT (81% good or excellent vs. 47%, respectively) and in the modified Tamai score (85% good or excellent vs. 71%, respectively). These results did not, however, reach statistical significance.

<p>| Table 5. Associations between lower scores of the primary outcome measures and type of transfer and injury patterns among thumb reconstruction patients |
|-------------------------------------------------|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th></th>
<th>Our ADL &lt;30</th>
<th>m Tamai ADL &lt;12.5</th>
<th>Sollerman &lt;70</th>
<th>m Tamai score &lt;60</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>5</td>
<td>1.00</td>
<td>1.00</td>
<td>3.87 [0.51–29.3]</td>
</tr>
<tr>
<td>Transfer</td>
<td>Great toe</td>
<td>7.11 [0.83–60.7]</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>2nd toe</td>
<td>1.00</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>3rd toe</td>
<td>1.00</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>No. of nerves/transfer</td>
<td>2</td>
<td>3.80 [0.31–47.2]</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.52 [0.33–6.96]</td>
<td>3.86 [0.46–32.4]</td>
<td>0.57 [0.06–5.69]</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>MTP joint incl. in the transfer</td>
<td>MTP +</td>
<td>0.75 [0.74–7.61]</td>
<td>1.82 [0.43–7.69]</td>
<td>1.69 [0.26–10.9]</td>
</tr>
<tr>
<td></td>
<td>MTP -</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Level of thumb amputation</td>
<td>1</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.60 [0.13–20.1]</td>
<td>1.65 [1.65–442]</td>
<td>2.30 [0.17–30.6]</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>No. of rays amputated</td>
<td>1-3</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>4-5</td>
<td>6.21 [0.87–44.6]</td>
<td>5.70 [1.20–27.1]</td>
<td>9.67 [1.43–65.4]</td>
</tr>
<tr>
<td>Method of amputation</td>
<td>Avulsion</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Crush</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Explosion</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>1.57 [0.08–29.4]</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Logistic regression models were used with the results expressed as odds ratio [95% CI].
A dash (–) indicates that there were no cases in this category.

1 See text (page 45) for clarification of the level of thumb amputation.

* P<0.05
probably influenced by the small number of patients in the more proximal amputation group (n=7).

The injured hand dominance did not affect the results according to the modified Tamai ADL (p=0.14), our hand ADL (p=0.934), the SHFT (p=0.14), or the modified Tamai score (p=0.223). Neither did gender (M/F 33/8) have an effect on the primary outcome measures.

The eleven patients who received a fair result in the Combined Score had on average more proximal amputation (mean level of amputation 2.3 vs. 1.8, respectively) and more often an amputation of the fingers (mean number of amputated rays 3.6 vs. 1.9, respectively) as well when compared to those with a good result.

5.2.2 Finger reconstruction patients

Nine of the 20 questions of the modified Tamai questionnaire were rated easy or quite easy. Likewise, nine patients reported managing ADL easy or quite easy. Similar to thumb reconstruction patients, picking up a coin or a pin; buttoning up; and using a safety pin were considered on average quite difficult. In addition, and quite expectedly, showing 'scissors', 'paper' and 'stone' was the most difficult task with only two patients reporting it easy. Twelve of the 15 patients reported managing ADL with no or only minor complaint according to our hand ADL questionnaire. Tasks causing the most difficulties, yet only a minor complaint, were handling small objects, strong grip, handle grip and fumbling in pocket.

Five of the 20 tasks tested with the SHFT were executed with slight difficulties, and the rest without difficulties. These slightly difficult tests were picking up a coin, using a screwdriver, turning hexagonal nuts, buttoning up, and pouring water from a milk carton. Three patients completed the test with slight difficulties, and the rest without difficulties. According to the modified Tamai score, there were 4 excellent, 8 good, 1 fair, and 2 poor results.

Patients with no functional finger spared by the initial amputation, scored worse in the Combined Score than those with at least some finger function left (mean 159 vs. 198, respectively). Further, none of the patients in the former group scored ≥ 172 if only one toe was used for reconstruction while all the patients who were reconstructed with two toes scored ≥ 172 points.
5.2.3 MC-hand reconstruction patients

None of the items in the modified Tamai questionnaire was reported as easy and 13 of the 20 questions were rated as either impossible or difficult. Most difficult tasks (rated on average impossible) were picking up a coin or a needle, using a safety pin or drinking from a palm. On the other hand, opening a door, pulling from a door handle, and grasping a soft material were considered quite easy. Overall, managing ADL was quite difficult for five and difficult for three patients. Handling small objects, fumbling in pocket, key pinching, and forceful rotating of objects were all considered to cause moderate complaint according to our hand ADL. Six out of eight patients expressed moderate complaint handling ADL.

The function of the reconstructed hand was considered normal or slightly diminished in picking up objects from a flat surface, opening and closing a zipper, lifting a 3 kg weight from a handle, using a screwdriver, pouring water from a pitcher and from a cup according to the SHFT. Altogether, there was one patient who finished the test without difficulties, four patients with slight difficulties, and three patients with great difficulties. The modified Tamai score median, reported from only five patients, was 63, which translates to a good result according to original scale by Tamai (Tamai et al. 1983).

According to the Combined Score, the two lowest results were from patients who had no functioning thenar muscles and the two best results were from patients who had thenar muscles intact.

5.2.4 AB-stump reconstruction patients

None of the questions included in the modified Tamai ADL were considered easy. Opening a door or a faucet, pulling a door handle and grasping a soft material were considered quite easy. Picking up a pin or a coin or using a safety pin was considered on average difficult. All in all, two patients managed ADL quite easily, and for the rest it was either quite difficult (n=5) or difficult (n=4). Similarly, handling coins or other small objects was considered a moderate complaint according to our hand ADL. Instead, strong gripping, getting dressed and managing oneself urinating and defecating were considered a minor complaint.

The reconstructed grip was too narrow to pour water from a milk cartoon or lift two wooden cubes (diameter 7 and 5 cm) in the SHFT. Turning a door handle 90° was executed without difficulties and folding a paper and placing it into an envelope and lifting a handset of a telephone and placing it back caused on average slight difficulties.
There was one patient, who passed the test without difficulties, the rest had either slight difficulties (n=2), great difficulties (n=1), or could only partially complete the test (n=7). According to the modified Tamai score, there was one excellent, two good, 6 fair, and two poor results.

The four patients receiving the worst results in the Combined Score all had amputations proximal to DRU joint. Hand dominance, simultaneous contra-lateral hand injury, method of amputation, or whether the patient had lost vision or not did not reflect to the Combined Score.

Patients who had amputation proximal to DRU joint (n=5) scored worse than those whose amputation was distal to it (n=6) in the modified Tamai ADL (median 4.8 (difficult) vs. 9.6 (quite difficult), respectively); our hand ADL (median 19 (moderate complaint) vs. 30 (minor complaint), respectively); and the SHFT (median 24 (partial completion) vs. 51 (slight difficulties), respectively). Further, patients with amputation proximal to DRU joint were less satisfied (median according to modified Tamai questionnaire 10 vs. 20, respectively) and more likely to be unable to work (three vs. two) than those with more distal amputations.

5.2.5 Donor site outcomes

The donor site results are presented from the whole patient material: 74 patients, 80 feet and 84 transferred toes. As seen in Table 6, the results of the primary outcome measures are quite similar in all the transfer groups, with a notice of slightly worse outcome in the double en block transfer group. However, no statistical testing was conducted between the results of different transfer groups because of too small group sizes. Our foot ADL and the AOFAS scale had a positive correlation (r=0.561, p<0.001).

According to our foot ADL, there were 60 (76%) feet which presented no complaint, 13 (16%) with minor complaint, four (5%) with moderate complaint and two (3%) with major complaint. Moreover, 62 (83%) of the feet received a good (≥78 points) result in the AOFAS scale. Both a good result in our foot ADL (>24 points) and in the AOFAS scale (≥78 points) predicted good patient satisfaction, less pain at rest or during exertion and less cold intolerance.

The median for each of the items in our foot ADL was 4 points equaling no complaint. Of the specific questions asked, running (n=14, 22%) and walking on uneven ground (n=12, 18%) were reported most often to cause moderate or major complaint. On the other hand, foot problems caused moderate or major difficulties in pursuing recreational activities in only 7 (9%) patients. Despite the overall good results in the AOFAS scale, there were at least some footwear restrictions in 18 (24%) patients.
5.3 Secondary outcomes

Most relevant secondary outcomes of the recipient site are presented in Table 7. One patient from the AB-stump reconstruction group is excluded from the data analyses of secondary clinician-based recipient outcomes because the indication for his reconstruction was a congenital anomaly (acheiria). Contralateral hand or foot was accepted as a control for the clinician-based outcomes only when it was uninjured.

5.3.1 Patient-reported

Pain, whether at rest or during exertion, was not a major issue to our patients. That is, only 11 patients (15%) reported pain at rest to be a moderate complaint, and 15 patients (20%) felt that pain at exertion was a major or a moderate complaint. Similarly, social acceptance, i.e. how patients felt other peoples’ reactions towards their reconstructed hands, presented no or minor complaint to most patients (n=65). Instead, cold intolerance posed a moderate to major complaint to nearly half of the patients (n=36). Patient satisfaction towards the reconstructive procedure was high. There were, however, two patients who, in retrospect, would not have selected the operation again and another five patients who were not satisfied. Further, patients rated their satisfaction towards the outlook of the reconstructed hand a median 81% of a maximum 100. Despite devastating amputations the patients suffered, 42 (57%) were able to return to their pre-injury occupation, and another 24 (32%) patients re-educated to another better suitable profession. Being unable to work due to the amputation, and regardless of the reconstruction, was more likely after an AB-stump (n=5, 45%) than other level amputation (n=3, 5%). This is quite natural considering the severity of the initial injury and the fact that these patients had often an associated contralateral condition (n=4) and, further, two patients had lost vision during the initial amputation injury.

Some of the secondary patient-reported foot outcomes are presented in Table 6. There were 16 patients who had no complaints about the donor site. Fifteen of them had had a single second toe transfer. Neuropathic symptoms (neuroma pain or sensory changes) were considered a minor or no complaint in 94–96% of the feet. Otherwise, cold intolerance was reported a major complaint in four feet and a moderate complaint in another 12 feet. Six patients with a second toe transfer and two with a great toe transfer were dissatisfied with the appearance of the donor foot. Patients with no or mild foot fatiguing (n=71 feet) scored clinically and statistically significantly better in our foot ADL (median 28 vs. 15.5, respectively, p<0.001) and the AOFAS scale (median 93 vs. 57, respectively, p<0.001) when compared to those with moderate or
Table 6. Primary and secondary foot outcomes of the three major groups of transfers

<table>
<thead>
<tr>
<th></th>
<th>Great toe</th>
<th>Single second toe[^1]</th>
<th>Second toe</th>
<th>Double toe</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our foot ADL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No or minor / moderate or major complaint (n)</td>
<td>5/0</td>
<td>33/2[^2]</td>
<td>20/2</td>
<td>62/5[^2]</td>
<td>4/1</td>
</tr>
<tr>
<td>AOFAS scale</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Md (range)</td>
<td>n/a</td>
<td>93 [52–100]</td>
<td>93 [57–100]</td>
<td>93 [52–100]</td>
<td>78 [55–80]</td>
</tr>
<tr>
<td>Good / fair</td>
<td>n/a</td>
<td>31/5</td>
<td>17/5</td>
<td>57/11</td>
<td>3/2</td>
</tr>
<tr>
<td>Walking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constricting scar</td>
<td>Yes/No</td>
<td>0/5</td>
<td>2/34</td>
<td>7/15</td>
<td>0/5</td>
</tr>
<tr>
<td>Standing on tiptoes</td>
<td>Able/not able</td>
<td>5/0</td>
<td>33/3</td>
<td>22/0</td>
<td>65/3</td>
</tr>
<tr>
<td>Callosities</td>
<td>No or symptomless/Yes</td>
<td>3/2</td>
<td>34/2</td>
<td>21/1</td>
<td>65/3</td>
</tr>
<tr>
<td>First ray alignment</td>
<td>Normal/fair/poor</td>
<td>n/a</td>
<td>15/19/2</td>
<td>10/10/2</td>
<td>30/3/5</td>
</tr>
</tbody>
</table>

[^1] Single second toe refers to a group of patients who had only one (the second) toe transferred.

[^2] One patient with a second toe transfer was unable to run because of a prosthesis of the contralateral foot.
Table 7. Secondary outcomes of the recipient site

<table>
<thead>
<tr>
<th></th>
<th>Scale</th>
<th>Thumb</th>
<th>Finger</th>
<th>MC-hand</th>
<th>AB-stump</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2nd toe [n=35]</td>
<td>1st toe [n=5]</td>
<td>Total [n=41]</td>
<td>[n=15/20]^1</td>
<td></td>
</tr>
<tr>
<td>Key pinch</td>
<td>Iq (%)</td>
<td>6.5 [0.5–12]</td>
<td>6 [3–10]</td>
<td>6.5 [0.5–12]</td>
<td>8.5 [2.5–13]</td>
<td>4.3 [2.5–7]</td>
</tr>
<tr>
<td>IP joint extension lag</td>
<td>% of control</td>
<td>42.5 [0–120]</td>
<td>45 [20–55]</td>
<td>45 [0–120]^7</td>
<td>115 [60–150]</td>
<td>60 [10–185]</td>
</tr>
</tbody>
</table>

^1 n=20 (transfers) for sensation and movement of the transfer, and 15 (patients) for the rest of the rows
^2 n=11 (transfers) for sensation and movement of the transfer, and 8 (patients) for the rest of the rows
^3 n=11 for patient reported values and 10 for clinician based values. One patient was excluded from the latter evaluation because his reconstruction was done for congenital anomaly
^4 Hypoesthesia is defined as lack of or poor quality of sensation
^5 According to the modified Tamai questionnaire. See text (page 53) for clarification
^6 VAS 0 = totally dissatisfied, 100 = totally satisfied
^7 18 patients in this group had had an MCP joint arthrodesis
severe foot fatiguing (n=9 feet). Similarly, no or mild pain during exertion (n=64 feet) was associated with clinically and statistically better function according to our foot ADL (median 28 vs. 18, respectively, p<0.001) and the AOFAS scale (median 93 vs. 72, respectively, p<0.001) when compared to moderate or severe pain (n=16 feet).

5.3.2 Clinician-based

The median key grip was 63% of normal contralateral hand for the thumb reconstruction patients and 40 to 41% after more proximal amputations. Key pinch was not markedly affected after finger amputation since thumb function was good in these patients. By comparison, the grip strength was near normal (84%) in patients with thumb reconstruction and about half (46%) in patients with finger reconstruction when compared to contralateral control hand. The amplitude and the breadth of the grip were inadequate to measure grip in patients with MC-hand or AB-stump reconstruction. All the 18 patients with either MC-hand or AB-stump reconstruction could hold size A4 paper indicating that the range and direction of the motion was adequate for pinching function. Despite fair results in both s2PD and m2PD, most patients (84%) could recognize j4.31 filament or better with their transferred toe. IP joint movement was a third of the control digit when the toe was transferred in thumb position. Great toe transfer regained better IP joint movement (median 45°, 45%) than the second toe transfer (median 25°, 33%). A second or third toe transferred to finger position recovered similar motion (median 28°), which, however, was only 16% of the control digit movement. IP joint extension lag was inevitable and more pronounced with a second (or third) toe transfer (range of median 18–58°) compared to great toe transfer (median 5°). None of the adjustments made for the second (or third) toe transfer during the operation (see Methods) or rehabilitation (dynamic extension splint) had an effect on the extension lag. Cylinder grip width (median 9, range 6–11) was measured from 55 patients, for the rest a 6 cm cylinder was too big to get a grip. The associations of some of the clinician-based physical variables and primary outcomes in the thumb reconstruction patients are presented in Table 8.

Contracting scar of the donor site was more common in patients where a hemipulp flap was included in the transfer 7/19 (37%) when compared to those without the hemipulp flap 5/56 (11%). Further, the first MTP joint TAROM was adequate (>75°) in 11 (58%) of the patients with a hemipulp flap included, compared to 43 (77%) of those without the flap. In total, 20 feet had some restriction of the first MTP joint TAROM (range 30–74°) and only one was assessed rigid (<30°). The restriction of TAROM of the first MTP joint (<75° vs. ≥75°) was associated with a worse result in the AOFAS
scale (78 vs. 93, respectively, p=0.002). The first IP joint TAROM was better preserved with only three rigid (<10°) joints. The worse the first ray alignment was judged, the more problems the donor feet presented with walking (p=0.041), running (p=0.002), foot fatiguing (p=0.044), our foot ADL (p=0.0042), and the AOFAS scale (p<0.001).

5.3.3 Radiological outcomes

Radiographic assessment of the recipient site was achieved from 72 patients, for whom 73 hands were reconstructed with 81 transferred toes. Further, 73 donor feet and 62 control feet were assessed with radiographs as well.

Radiographic results of the recipient site are presented in Table 9. The difference in the follow-up time, pain at rest or during exertion between patients with no or mild and moderate or severe osteoarthritis of the transfer IP joint was not substantial. Instead, patients with moderate to severe osteoarthritis of the transfer IP joints were older (median 51y, range 23–66) than those with no or mild osteoarthritis (median 43, range 12–70) and this difference was statistically significant (p=0.038). Five (19%) of the transferred MTP joints displayed moderate and the rest had no or mild osteoarthritis. Patients with normal bone structure were of same age (median 44 y both), had slightly longer follow-up (median 214 months vs. 170 months, respectively) and expressed less pain during exertion (no or minor 86% vs. 69%, respectively) than those with mild to marked osteopenia. In thumb reconstruction patients, the presence of osteopenia (mild or marked vs. normal bone structure) did not produce clinically significant differences in primary outcomes.

Radiographic results of the donor site are presented in Table 10. According to the radiographic grading of the HVA, there were 31 (46%) normal, 14 (21%) mild, 21 (31%)

---

Table 8. Physical variables and primary outcomes in thumb reconstruction patients

<table>
<thead>
<tr>
<th>Cylinder grip width</th>
<th>Key pinch</th>
<th>Grip strength (Jamar)</th>
<th>m2PD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our ADL</td>
<td>0.57 [&lt;0.001]</td>
<td>0.72 [&lt;0.001]</td>
<td>0.63 [&lt;0.001]</td>
</tr>
<tr>
<td>Modified Tamai ADL</td>
<td>0.57 [&lt;0.001]</td>
<td>0.65 [&lt;0.001]</td>
<td>0.42 [0.006]</td>
</tr>
<tr>
<td>SHFT</td>
<td>0.51 [0.001]</td>
<td>0.64 [&lt;0.001]</td>
<td>0.52 [&lt;0.001]</td>
</tr>
<tr>
<td>Modified Tamai score</td>
<td>0.44 [0.006]</td>
<td>0.60 [&lt;0.001]</td>
<td>0.31 [0.054]</td>
</tr>
<tr>
<td>Satisfaction (m Tamai)</td>
<td>0.17 [0.292]</td>
<td>0.39 [0.011]</td>
<td>0.10 [0.542]</td>
</tr>
</tbody>
</table>

Showing the Spearman correlations (r) with p-values [p] between physical variables and primary outcome measures and satisfaction according to modified Tamai score in the thumb reconstruction patients.

1 m2PD (≤10 mm vs. >10 mm) presented according to Fisher’s exact test with p values (p)
Table 9. Radiographic results of the recipient site

<table>
<thead>
<tr>
<th>Thumb(^1)</th>
<th>Finger</th>
<th>MC-hand(^2)</th>
<th>AB-stump</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCP/MTP</td>
<td>17/8</td>
<td>19/1</td>
<td>1/9</td>
<td>0/9</td>
</tr>
<tr>
<td>Osteopenia in the transfer hand</td>
<td>1</td>
<td>26</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>13</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Transfer IP joint osteoarthritis</td>
<td>1</td>
<td>28</td>
<td>15</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>12</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MCP joint osteoarthritis</td>
<td>1</td>
<td>9</td>
<td>17</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Osteopenia classification: 1= no, 2= mild, 3= marked
n/a = not applicable
Osteoarthritis classification (according to Gahunia et al. 1995): 1= no or mild, 2= moderate, 3= severe
\(^1\)There were 16 thumb reconstruction patients with MCP joint arthrodesis. One patient had deformed transfer IP joint excluding the estimation of osteoarthritis.
\(^2\)There was one patient in this group with MCP joint arthrodesis

Table 10. Radiographic results of the donor site

<table>
<thead>
<tr>
<th>I MTP osteoarthritis: no or mild</th>
<th>Moderate or severe (n)</th>
<th>Hallux valgus(^a)</th>
<th>IMA I–II(^b)</th>
<th>IMA I–III(^b)</th>
<th>Width of the forefoot (mm)</th>
<th>Osteopenia: no/mild (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Donor feet (n=73)</td>
<td>53/15(^1)</td>
<td>15.5 [0–53](^1)</td>
<td>8 [1–16](^2)</td>
<td>8 [1–21]</td>
<td>78 [58–98]</td>
<td>68/5</td>
</tr>
</tbody>
</table>

IMA= intermetatarsal angle, MT + = metatarsus present in the foot, MT -= absent or very short metatarsus, xx= cannot be measured
\(^1\)n=68 because patients with great toe transfers were excluded
\(^2\)n=53 because 20 patients with second toe transfer had a very short or absent second metatarsus
\(^3\)n=51 because two of the control feet were excluded because one was prosthesis and the other had a phalangeal amputation
\(^4\)n=33 because 20 patients with second toe transfer had very short or absent second metatarsus
\(^5\)n=33 because 20 patients with second toe transfer had very short or absent second metatarsus
moderate and two (2%) severe deformities among the donor feet. Similarly judged, the control feet displayed 40 (66%) normal, nine (15%) mild, and 12 (19%) moderate deformities. There were 11 (18%) patients who had increased HVA (>15°) only in the donor feet, most likely due to the transfer operation. In addition, there were 25 patients who had the HVA at least 4° greater in the donor than the control feet, which seemed to be associated with poorer result in the AOFAS scale (median 78 vs. 93, p=0.069). The IMA I–II grading allocated 31 (58%) normal, 14 (26%) mild and 8 (16%) moderate deformities of the donor feet. While, 24 (39%) of the control feet were judged normal, 37 (60%) had mild and one (1%) had moderate deformity. Interestingly, there was no increase in the IMA I–II or IMA I–III in the donor feet compared to control (Table 10). Concordantly, the forefoot was actually narrower in the donor feet. Both these results were noted in the whole patient material and in patients who had only a single second toe transfer. The difference is not significant, but more importantly, there was no widening of the forefoot because of the toe transfer. Patients with moderate or severe first MTP joint osteoarthritis (n=15, median age 55y) were on average older (p<0.001) than those with no or mild arthritis (n=53, median age 41y). Moreover, moderate or severe osteoarthritis was associated with first ray malalignment (p=0.023) and seemed to be related to worse score in the AOFAS scale (median 80 vs. 93, p=0.065), but not with pain (whether at rest or during exertion). Moderate or severe first MTP joint osteoarthritis was more common in the donor than the control feet, and 7 of the 15 patients had the condition only in the donor feet.

5.3.4 Complications

Complications are defined as events occurring early on in the perioperative period; usually within the time of primary wound healing. There was one systemic complication: a deep venous thrombosis in the leg where a second toe was removed in a 31 year old male patient. He was treated with an anticoagulant and suffered no further consequences of the thrombosis. Another patient had a transient peroneal palsy due to prolonged tourniquet time (twice 2h). The ultimate complication, a failure to re-establish and maintain sufficient circulation leading to necrosis of the transfer has been covered earlier in section 5.1 Survival. Most frequent complications and secondary operations are presented in Table 11.

There were four immediate vascular complications. One of them was relieved with removal of hematoma, but the rest required emergency re-operations. One of the patients needed three re-operations to restore circulation and further three operations
to resect and cover a loss of the other toe of the double en-block toe transfers. Two of the six recipient site infections were related to K-wires.

A total of 16 patients had problems with donor site wounds. In eight of these cases, an infection was detected and treated with an oral antibiotic. Eleven late procedures, performed during an outpatient clinic visit, were required to close the wounds. In addition, five wounds required a STSG. Patient smoking and using a STSG to close the donor site wound were both related to wound healing problems. That is, 62% (n=10) of the patients with wound healing problems were smokers, whereas 38% (n=23) of those who’s wounds healed uneventfully smoked. Further, nearly half of the feet (6/13) where the STSG was used for donor site closure had problems with wound healing, while only 15% (10/67) of directly closed wound displayed healing problems. Those exhibiting wound healing problems scored statistically and clinically significantly worse in the AOFAS scale compared to those without problems (78 vs. 93, respectively, p=0.004), and reported more problems with walking (median 3 vs. 4, respectively, p=0.001).

5.3.5 Secondary operations

There were four predetermined secondary recipient site procedures (Table 11). Other than that, a total of 32 secondary procedures of the recipient site were performed to 19 (26%) patients. Removals of K-wires are not included in this category. In contrast, only four patients required five secondary operations to the donor site.

Table 11. Complications and secondary operations

<table>
<thead>
<tr>
<th></th>
<th>Hands (n)</th>
<th></th>
<th>Feet (n)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Patients</td>
<td>Operations</td>
<td>Patients</td>
<td>Operations</td>
</tr>
<tr>
<td><strong>Complications</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vascular</td>
<td>4</td>
<td>8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Infection</td>
<td>6</td>
<td>0</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>Wound dehiscence</td>
<td>2</td>
<td>2</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Tendon</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Scar revision</td>
<td>7</td>
<td>9</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Osteotomy</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Tendon reconstruction</td>
<td>6</td>
<td>7</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Tenolysis</td>
<td>6</td>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Nerve resection</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Arthrodesis</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Nerve reconstruction¹</td>
<td>1</td>
<td>1</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Syndactyly release¹</td>
<td>3</td>
<td>3</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

* n/a = not applicable
* ¹ These were predetermined secondary operations
Comparison of the results between this study and those of the literature presented earlier on in this academic dissertation is hampered by different approach to the subject, small and heterogenic patient populations, and lack of widely accepted outcome measures. The discussion is divided into recipient site, donor site, complications and secondary operations, and then to a summary weighing the benefits and disadvantages of these types of toe transfer procedures. Finally, weaknesses of this study are considered.

6.1 The recipient site

The patient population was divided based on the Vilkki classification of no-finger hand (Vilkki 2001). It highlights the important elements of the hand that are needed for gripping: adequate finger function can be reconstructed when there are at least two intact MCP joints spared, first CMC joint and thenar muscles (especially the AdP muscle) are vital for thumb function. Toe transfers have, in essence, the ability to flex and to extend. The unique feature of the thumb is opposition and it is possible only when first CMC joint is intact and fluent only when thenar muscles are functioning sufficiently. Without the aforementioned prerequisites, in more proximal amputations, the goal of reconstruction is more basic function of the hand: pinching. A movable radio-carpal joint brings in an additional motor for the reconstruction. That is, movement of the wrist into flexion and extension can be used synergistically, through tenodesis effect, to open and close the pinch reconstruction. The classification, therefore, guides in targeted reconstruction of grip.

The survival of the transfers is quite comparable between our patient population and that of the literature. There was a failure of one of the two toes transferred as a block among our patients. The reported survival rates for example for thumb reconstruction patients vary between 80.8 and 100 % (Lin et al. 2011). However, given the small patient populations, a single failure can change the survival rate considerably.
6.1.1 Primary outcomes

Since the indication for toe transfer in this patient population was to restore or enhance the ability to grip, measuring function of the hand was the primary outcome. Function was evaluated with questionnaires and tests that evaluate different forms of hand use and gripping ability both patient-reported and clinician-based. In addition, a wide set of secondary outcomes were reached. Emphasis was on the patient-reported, rather than clinician-based, methods. The patient is, in fact, the one to judge the success of the reconstruction.

The measured function was dependent on the extent of the initial injury. That is, patients with thumb or finger reconstruction scored better in primary outcomes compared to patients with either MC-hand- or AB-stump reconstruction (Table 4). There was no marked difference between the results of thumb or finger reconstruction patients. Interestingly, AB-stump reconstruction patients scored better in the patient-reported but worse in the clinician-based primary outcome measures than the MC-hand reconstruction patients. This may be, at least partially, explained by the fact that AB-stump reconstruction patients had more often a bilateral condition affecting the hand use. It is theorized that, when the other hand is intact it takes more dominant role in managing the ADL, and, as a consequence, the reconstructed hand is felt more awkward and less needed. Still, this finding may be purely coincidental due to small number of patients in each of the groups.

In more detail, the extent of the injury within the thumb- and the finger reconstruction groups influenced the primary outcome. That is, thumb reconstruction patients with radial one to three rays amputated scored better in the SHFT and the modified Tamai ADL than those with amputation four to five rays. Moreover, the likelihood of returning to pre-amputation occupation was higher in patients who had intact little and ring fingers (odd ratio 4.9, 95% CI 1.08–22.6). This emphasizes the importance of intact ulnar aspect of the hand to work in liaison with the reconstructed thumb. Also, the level of thumb amputation seemed to influence the functional recovery. The result concerning the effect of the extent of the amputation both towards the ulna to involve the other fingers and proximally along the thumb ray are in accordance with those presented in the literature (Leung 1983, Poppen et al. 1983). Similarly, patients in the finger reconstruction group, who had some finger length and function spared scored better in both the patient-reported primary outcomes and the Combined Score than those who had lost all fingers in the initial amputation. Further, those patients with no fingers left, who were reconstructed with two toes scored better in the Combined Score than those reconstructed with a single toe. In conclusion, transferred toes are, still, inferior to original fingers, and double toe reconstruction should be preferred over
a single toe reconstruction in patients with all fingers amputated. The latter conclusion is in agreement with the recommendations made by Ma et al. for the hand with thumb but no fingers (Ma et al. 1996).

In the thumb reconstruction patients, crush (n=15) and explosion (n=6) amputations predicted poorer outcome compared to avulsion (n=12) amputation according to modified Tamai ADL. This may reflect the fact that avulsion amputation most often affected only the thumb ray and spared the first CMC joint and the thenar muscles. There were three patients who had had a surgical amputation of the thumb. These patients scored somewhat better in the primary outcomes, reported fewer symptoms, and were more pleased with the outlook of the transfer than the whole of thumb reconstruction population.

Interestingly, the number of nerve reconnections in thumb reconstruction patients had an impact on the function according to SHFT. That is, patients with four nerves reconnected scored clinically and statistically significantly better than those with only two nerve repairs. Anastomosing the dorsal nerves as well may increase sensory input about the posture and movement of the transferred toe and so improve its usability.

In general, the function of the hand after a thumb or finger reconstruction was good. Yet, tasks requiring precision, like manipulating small objects, did pose some difficulties to our patients according to the SHFT, modified Tamai ADL, and our hand ADL. Similar results were reported for thumb (Poppen et al. 1983, Frykman et al. 1986) and for finger reconstruction patients (Gordon et al. 1985). However, Chung and Wei could not find significant differences, in executing the Jebsen-Taylor test between hands with thumb reconstruction and their control (Chung and Wei 2000). Interestingly, tasks in the SHFT requiring rapid grasp and release (like turning hexagonal nuts and using a screwdriver) were the most difficult in patients who had had finger reconstruction. On the other hand, the reconstructed grip seemed to be wide enough for span grasp (manipulating larger objects like wooden cubes, milk cartoons, or a lid of a jar), strong and stable enough for power grasp (like hammering or strong gripping), and accurate enough for key pinching.

The goal for MC-hand and AB-stump reconstruction is to achieve a simple pinch. The size of the object to be manipulated may become an issue. That is, wooden cubes (of the SHFT) or a milk cartoon were often too large to get a grip, or using scissors would have needed a larger span of grasp. Coins and keys could be picked up and the use of a zipper was possible, though not without difficulties. Quite naturally the hand function in these patients was modest compared to control hand or to patients who had undergone thumb or finger reconstruction. The extent of the injury expressed according to the Vilkki (Vilkki 2001) or the Wei (Wei et al. 1997a) classifications was not related to the measured function in patients MC-hand reconstruction. Interestingly, patients
in the Vilkki C group seemed to be more satisfied with the reconstruction than those in the group B (satisfaction according to the modified Tamai score 17.5 vs. 10, respectively). Instead, the level amputation in the AB-stump group (see page 46 for explanation) did seem to relate to the primary outcomes. That is, patients who had had amputation proximal to the DRU joint did worse than those with amputation distal to the joint. The literature reporting the function of these patients is sparse and rather inaccurate with comments like “all regained prehensile function” (Wei et al. 1999) or “92.2% of patients recovered hand function” (Yu and Huang 2000) making the comparison of results impossible. Since function was not measured both pre- and post-reconstruction, it is difficult to state unambiguously the precise enhancement of function the toe transfer has produced. There was, however, one patient in the AB-stump group who had a bilateral mid-forearm level amputation with only one side reconstructed. Despite the reconstructed hand scoring poorly in tests measuring function, the other, non-reconstructed, hand was far worse receiving only two points in the SHFT. Besides this patient, it was clearly shown that patients used the created pinching ability in everyday life.

6.1.2 Secondary outcomes

The secondary patient-reported outcomes of the recipient site are seldom discussed in the scientific literature concerning toe transfer patients. Pain, even though not a major issue to these patients, can still be expected even years after the initial trauma. Our study setup does not allow us to differentiate between the amputation and the toe transfer as the cause of the pain the patients report. Nonetheless, most likely the injury causing the amputation, rather than the toe transfer, is the origin of the pain. It is theorized that, resecting the neuromas and re-connecting the nerves of the amputation stump to those of the toe transfer could alleviate neuropathic pain in some instances. Cold intolerance was probably the most annoying secondary symptom, even more so a concern in the Nordic climate.

Patient satisfaction in general towards the final result of the reconstruction and more specifically towards the outlook of the reconstructed hand was high in all the four reconstruction groups. Only two patients would not want, in retrospect, the reconstruction again. High patient satisfaction has been reported by other authors as well (Yu and Huang 2000, Leung 1980a). Despite MC-hand and AB-stump reconstruction patients not performing as well as the thumb- or finger reconstruction patients in the test that measure function, satisfaction did not show such noticeable differences. This indicates that the tests used to measure function did that with
reasonable accuracy and that patients had realistic expectations of what could be achieved in each case. Patients were able to return to their pre-amputation employment or changed to a lighter or easier occupation with high frequency. For instance, all the patients who had had reconstruction of a MC-hand amputation were employed. Being able to find an employment is, of course, a multifactorial condition. One patient in our series suffered a bilateral upper extremity amputation and lost his vision in an explosion injury during military service. The other hand was reconstructed at AB-stump level and the other with a toe-to-thumb transfer. Without vision, his only normally sensible finger for reading braille was ulnar aspect of the ring finger. Even in this condition, he was self-employed illustrating strong motivation which is the major driving force in recovery.

The scientific literature concerning toe transfer patients is packed with reports of motion, sensation and strength. If nothing else, these parameters are offered. Often they are misinterpreted to equal function. Due to reporting of physical parameters from a heterogenic patient population as the result of a single group, it is often difficult to compare our results to those of the others. Our results concerning the physical variables in the different reconstruction groups fall slightly short compared to those presented in other publications for thumb reconstruction (Lin et al. 2011); for finger reconstruction (Leung 1986, Foucher and Moss 1991); for MC-hand reconstruction (Tsai et al. 1981); and for mixed indications (Gu et al. 1997). We could demonstrate a statistically significant positive correlation between cylinder grip width, key pinch, grip strength and m2PD and primary outcomes, but not with patient satisfaction, in thumb reconstruction patients. Good key pinch was also related to being able to return to pre-amputation occupation. These physical variables are not same as function but they certainly contribute to it.

6.2 The donor site

The donor site outcome was assessed with patient-reported, clinician-based and radiographic evaluation. From the two first mentioned, two scores (our foot ADL, and the AOFAS scale) were calculated. Despite heterogenic patient population, certain subgroups of patients could be set apart and discussed in relation to expected donor site defect.

Overall, our patients had good functional recovery of the donor site after toe transfer procedure as was the case with Yang and Gu’s patients (Yang and Gu 2000). A good result in our foot ADL or the AOFAS scale predicted good secondary patient-reported outcome.
The length of the metatarsus included in the single second toe transfer did not affect the donor site defect. Contrary to Gu et al. (Gu et al. 1997) no substantial differences could be detected in the patient-reported or clinician-based parameters, in the AOFAS scale, or patient satisfaction between patients with intact or short/absent second MT. Inclusion of the hemipulp flap from the fibular side of the great toe was related to restricted first MTP joint movement and more scar contraction but not with first ray malalignment. Similar to Chung and Wei (Chung and Wei 2000), a statistically insignificant superiority of the second toe transfer over the great toe- and second-third en block transfer groups was detected in patient-reported and clinician-based outcomes. The number of patients in each subgroup is too small to draw solid conclusions from this observation.

Toe transfer definitely affects the perceived function of the donor foot. That is, only 16 of our patients were symptom-free. These manifestations are in most cases mild, which results in good patient satisfaction. Similarly high satisfaction could be detected in our patient population (88%) as did Yang and Gu (Yang and Gu 2000), even though their high rate (86%) of full recovery in six months could not be matched.

Correct first ray alignment was related to better functional outcome (according to our foot ADL and the AOFAS scale) and less symptoms with walking, running or foot fatiguing. The donor feet of our patients displayed more first ray malalignment (n=44, 59%) than was reported by others (Gu et al. 1997, Yang and Gu 2000). The restricted first MTP motion (detected in 21 feet, 28%) can be an independent nominator for poorer function according to the AOFAS scale, but in can also coincide with an increased first MTP joint arthritis or a pathologically increased HVA.

There is a raised risk of developing pathologically increased HVA (>15°) after toe transfer procedure, an observation shared by Bayaert et al. (Bayaert et al. 2003). Eleven (18%) of our patients with a single second toe transfer had this condition only on the donor site. Further, increased HVA seemed to be related to worse result in the AOFAS scale. Similarly, a third of the patients categorized as having moderate or severe hallux valgus (according to Coughlin 1996) displayed worse functional outcome according to the AOFAS scale. Interestingly, no widening of the forefoot could be detected in our patients and, further, increased IMA I–II or IMA I–III were not related to patient-reported or functional outcomes. The first MTP joint osteoarthritis was related to patient age, first ray malalignment and it was more common in the donor than the control feet. Moreover, it seemed to be related to worse functional result but not with pain. Contrary to Tiamfook et al. (Tiamfook et al. 1994), our patients did not show frequently osteopenia of the donor foot. When present, it was also found in the control foot.
6.3 Complications and secondary operations

Vascular complications, although rare, resulted in six additional operations (three attempts to fix the problem and three revision amputations) to one patient. Infections of the hand and the foot were always superficial and no intravenous antibiotics were needed. Wound healing problems were quite common among the donor feet. They were more common among smokers and in feet where the donor wound was closed with the help of a STSG. Wound healing problems predicted poorer functional outcome and more problems with walking.

Despite meticulous planning and execution of the transfer operation, 26% of our patients underwent a secondary procedure to the recipient site. Most of these were done to improve the scar or tendon function. Our frequency of secondary operations falls in between the two extremes reported in the literature; 14.3% (Yim and Wei 1995) and 70% (Coskunfirat et al. 2005). The indications for these procedures are similar to our series. As stated before, the frequency of secondary operations is patient and surgeon dependent and, therefore, not a very good indicator of the success of the reconstruction.

6.4 The recipient site gain and the donor site loss

To comprehensively appraise the results of grip reconstruction with microvascular toe transfer, one must weigh the benefits to the recipient site and the disadvantages caused to the donor site. A hand without a thumb lacks opposition and pinching between the long fingers is far from that of a thumb and a long finger. A hand with a thumb but no fingers is similarly handicapped allowing only simple and poorly functioning pinch. A metacarpal- or antebrachial stump-level amputated hand has no possibility of prehension. Our patient population consists of patients desperately in the need of augmentation of grip. We have been able to show that in the majority of cases, the toe transfers have clearly been put to use by the patients and we can, indirectly, assume that the function of the hand has increased due to the reconstruction. We can observe good functional outcome, high patient satisfaction and high rate of employment in our patients.

But all this does not come without a price. We subject over a quarter of our patients to a mean of 1.7 secondary operations. Almost 80% of our patients have some complaints about the donor site, a quarter of patients have some restrictions about the footwear, three percent will have major complaints with walking and eight percent with running, 18% will develop pathologically increased HVA only on the donor site.
There was a positive correlation between some of the functional outcomes of the recipient and donor site. The outcome of the function of the hand was affected by the extent of the initial trauma. However, the donor feet were all the same prior to the transfer procedure. There were six patients who received poor results in almost all the patient-reported and functional outcomes of the recipient as well as the donor site. This leads to a conclusion that the outcome of the hand influences the donor site defect.

To conclude, patients with obvious impairment of gripping ability are best candidates for microvascular toe transfer procedure. It would seem unjustified to subject patients to the burden of complications, secondary operations and the resultant donor site defect for merely cosmetic indications. In each case, a balance should be sought between sufficient gain and the least amount of harm. With this in mind, a second toe transfer appears ideal for thumb and AB-stump reconstruction. It is a versatile graft offering increased reach, with inclusion of the MTP joint and the metacarpal bone, and has acceptable donor site defect. A single second toe transfer may even be adequate for the MC-hand reconstruction as well. So far, no study has shown superiority, and therefore justification, of reconstructing a tripod pinch with three toe transfers over a pinch reconstruction with a single toe transfer. In contrast, a hand with thumb but no fingers is probably better off with two rather than a single toe transfer.

Restoring strong key pinch and, when possible, grip strength together with good opening ability of the first web space and adequate sensation should be pursued with the reconstruction. Adequate sensation may need the reconstruction of the dorsal nerves, in addition to the volar, as well. Patients with disabling neuropathic pain, due to the initial injury, will continue to have difficulties in using the hand even after the reconstruction. The donor site should be dealt with the same level of meticulousness as the recipient site. That is, wound healing problems of the donor site will continue to haunt the patient for years to come. These are best avoided with direct wound closure and encouraging the patient to stop smoking. Foot elevation and walking plaster cast were used in our patient postoperatively to ensure donor site wound healing.

6.5 Weaknesses of the study

This study is retrospective in nature and, therefore, the information about the initial amputation, reconstructive operation and postoperative care are subject to flaws. What is more important, no estimation of the function of the recipient or the donor site was done prior to the toe transfer operation. Subsequently, only an indirect conclusion can be made of the recipient site improvement or the donor site defect. Due to the long time elapsed from the reconstruction to the commencement of the study, no estimation
of pre-reconstruction function based on the patients’ recollection was done. Further, a possible selection bias impairs the comparison of the results of certain subgroups. That is, a patient to be selected to finger reconstruction with a single or a double toe transfers or to thumb reconstruction with a great or a second toe transfer may have been influenced by uncontrolled factors that also affect the outcome of the reconstruction. Lastly, a control group was lacking. However, with these kinds of rare and devastating injuries, a reasonable control group that has no selection bias is impossible to get.

Another selection bias may arise from the number of drop-outs. We were able to include into the study 74 (80 feet) of the 98 (103 feet) possible patients. For example, eight of the eligible 12 MC-hand reconstructed patients attended the study. Some of the patients had deceased, others could not be reached, and there were six patients who announced that they did not want to participate. The 76% participation rate can still be regarded as acceptable considering the long time elapsed from the intervention and the fact that these patients are spread all around Finland. As a sign of the special care the patients had received and the commitment they had, one patient flew from Stockholm just to participate in the study.

To give a more realistic picture of the outcomes and to avoid the excess heterogeneity, we were compelled to divide our patient population into four different groups based on the targeted reconstruction. These groups were further divided into subgroups better describing the extent of the amputation. All this led to small group sizes. That is why methods of statistical analyses were applied only for thumb reconstruction patients and when assessing donor site defect of the entire patient population. Small group size also restricts possibilities of drawing conclusions of what factors might have influenced the outcome.

Two of the tests used to measure primary outcomes, the modified Tamai score and the AOFAS scale, were translated to Finnish. However, no validation of the tests to Finnish language or the population was done. We had the instruction manual of the SHFT but it is has some inaccuracies making our test kit and protocol unique. This impairs the comparability of our results with those from other investigators using the same tests. None of the tests used in this study to measure function have been through clinimetric evaluation. We do not know what the internal or external validity of these tests are. Continuous variables displayed skewed distributions. This may due to limited sample size (in the case of physical variables) or reflect the inaccuracy of the tests to measure function. Some of the categorical variables displayed a roof effect, which means they were not able to differentiate from each other patients who were doing well. For example, highest scores were reported from a median of 54% (range 16–91%) of the specific questions asked in our hand ADL from the thumb- and finger reconstruction patients.
7 SUMMARY AND CONCLUSIONS

1) A single second toe transfer placed on the side of the radius was sufficient to create functional pinch grip in patients with AB-stump amputation (I).

MC-hand level amputation was reconstructed in 7/8 times with a single second toe transfer. Similar to AB-stump reconstruction, high patient satisfaction and adequate functional reconstruction was recorded (II).

Thumb reconstruction was achieved in most cases with the second toe transfer. Functional, clinician-based and patient-reported results were good in the majority of cases (III).

Patients with finger reconstruction scored similarly well in the functional-clinician-based and patient-reported assessments as the thumb reconstruction patients. However, the transferred toes were still inferior to original fingers. In a hand with no fingers left better results are achieved after two than a single toe transfer (IV).

2) There was only one failure among the 85 transferred toes (74 patients). Donor site wound healing problems result in long-term problems. 26% of the patients needed secondary operations of the recipient site (I–IV).

3) The extent of the amputation injury had an effect on the outcome. That is, thumb and finger reconstruction patients had better function than MC-hand or AB-stump reconstruction patients. Further, within the thumb, finger and AB-stump reconstruction groups the extent of the injury influenced functional outcomes (I–IV).

4) Most patients had at least minor donor site consequences after toe removal. A quarter of patients had some footwear restrictions and almost a fifth of the patients developed pathologically increased HVA (V).

5) With correct patient selection, the donor site defect is overcome by the recipient site gain. Only two patients would not, in retrospect, want the toe transfer procedure done (I–V).
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Lars Holm provided the illustrations of the Wei- and the Vilkki classifications to the original article II and to this academic dissertation, the former of which prompted positive comments from the otherwise critical reviewers.

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I have been fortunate to be able to work in both Tampere and Turku University hospitals. My role evolved from a young apprentice in Tampere to an independent specialist in Turku. During these years I have been surrounded by enthusiastic colleagues, skilled surgeons, determined leaders, and friends. I have tried to pick up things from the lot.

I still remember the first day as a trainee in TAYS. I was shocked by the gap of knowledge I found between me and my seniors. I “grew up” with Camilla Hellevuo, sharing the joys and adversities of the internship. That is why you became the closest. I observed a very high level of clinical knowledge and surgical skills of Jouni Havulinna and Pasi Paavilainen. A craftsmanship still unachieved by me. I was guided by silent knowledge and miles of experience by Tuula Salmi and Timo Viljakka. I was very receptive. I am grateful to you for all those years.
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The hand surgical unit in Turku grew from a single to a four specialist clinic. I’m honoured to have Nina Tamminen, Hanna-Stiina Taskinen and Heidi Vastamäki as my fellow workers. I feel there is an atmosphere of mutual respect and support among us. Looking from the ground level, the well-being in a workplace is highly dependent on the skills and personality of your bosses. I cannot imagine better people for that than Hanna-Stiina and Petri Virolainen. Two layers of good management protect the working man from many ordeals.

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This project started at 2006, about the same time I met my future-to-be wife Anna. She has stood by me all these years giving me support and encouragement. We have a wonderful daughter, Saara, who has taught me a lot. I thank you Anna and Saara for bringing balance and unparalleled joy into my life.

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

Simo K. Vilkki*, Tero Kotkansalo

Department of Hand and Microsurgery, Tampere University Hospital, FIN 33521 Tampere, Finland

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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.

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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
hand reconstruction models for wrist amputees. They used the 1970's the Chinese microsurgeons developed microsurgical methods allowed a direct free tissue transfer and the Krukenberg procedure has become less popular. In the experience gained from 13 cases using this last mentioned method with its modifications is the basis for this article.

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. 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. 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. 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. 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. 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.

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
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.

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. 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.
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 ultrasound 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 antebraehial 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.

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 antebraehial 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 antebraehial sensory donor nerves. The extrinsic tendons are dissected in suitable lengths.

![Figure 3](image3.png) The arteries and nerves are located preoperatively.

![Figure 4](image4.png) It is important to plan preoperatively the extent of bone resection and the available muscles to be used.
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 5** Bone resection shown schematically in longitudinal and transverse plains.

**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.
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 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.

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. It consists of a questionnaire and a

<table>
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<th>Patient no</th>
<th>Age at injury (y)</th>
<th>Sex</th>
<th>Injury type</th>
<th>Level of amputation</th>
<th>Other injuries</th>
<th>Injury environment</th>
<th>Follow-up months</th>
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<tr>
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<td></td>
<td>2</td>
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</table>

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

<sup>a</sup> I and V ray amputation and median nerve injury.

<sup>b</sup> I-IV CMC level injury with only poorly functioning V ray left.

<sup>c</sup> metacarpal hand type amputation.

<sup>d</sup> bilateral congenital acheiria.
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. To evaluate donor site defect and related problems we used the AOFAS scoring for forefoot.

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.

<table>
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<th>Table 2 Operation data</th>
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<td>11</td>
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<td>13</td>
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</table>

Average 11\(^a\)

\(\text{DMTA} = \text{dorsal metatarsal artery}, \text{PMTA} = \text{palmar metatarsal artery.}\)

\(^a\) excluding patient no 13.

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.

Table 2 Operation data

<table>
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<tr>
<th>Patient no</th>
<th>Interval to reconstruction (months)</th>
<th>Toe artery</th>
<th>Recipient artery</th>
<th>No of nerves reconstructed</th>
<th>No of tendons reconstructed</th>
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</tbody>
</table>

Average 11\(^a\)

\(\text{DMTA} = \text{dorsal metatarsal artery}, \text{PMTA} = \text{palmar metatarsal artery.}\)

\(^a\) excluding patient no 13.
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 inter-mEDIATE 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

<table>
<thead>
<tr>
<th>Patient no</th>
<th>Complications:</th>
<th>Flap survival</th>
<th>Emergency re-operations</th>
<th>No of secondary operations:</th>
<th>The complication or secondary operation performed</th>
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</tbody>
</table>

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.
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 (28 to 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 to 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 to 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 to 14, 25) points. There is a clear correlation between the two ADL questionnaires (Spearman $r = 0.887$). 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.

The Sollerman hand function test

<table>
<thead>
<tr>
<th>Patient</th>
<th>Key pinch (kg): transfer</th>
<th>Key pinch (kg): control</th>
<th>S-W filaments: transfer</th>
<th>S-W filaments: opposing surface</th>
<th>TAM: transfer</th>
<th>TAM: control</th>
<th>Sollerman score: transfer</th>
<th>Sollerman score: control</th>
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<td>2a</td>
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<td>95</td>
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<td>56</td>
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<td>75</td>
<td>36</td>
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<td>85</td>
</tr>
</tbody>
</table>

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, 5, 8, and 9 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.
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.
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

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<tr>
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</tr>
<tr>
<td>4&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td>Average</td>
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<td>27</td>
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</tbody>
</table>

<sup>4</sup> = 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.

<sup>a</sup> both patients lost their vision at the trauma.
or as early as possible for best results. Sometimes it is good
to remember this technique already in emergency replanta-
tion 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 amputa-
tions are quite comparable. However the infrequent need
of this type reconstruction makes the learning and experi-
ence 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 Soller-
man 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 amputa-
tion 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 experi-
enced 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 ac-
tivate the artificial limb functions even more precisely than
a myoelectric steering. Less optimal results correlated to
the type of injury (electrical burn pat. no. 7) or to the short

<table>
<thead>
<tr>
<th>Patient no</th>
<th>Sollerman test score (0–80)</th>
<th>Our ADL (11–44)</th>
<th>ADL from Tamai Scoring system (0–20)</th>
<th>Satisfaction (0–20)</th>
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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. 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. 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 immunosuppression 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.

Acknowledgements

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References

The functional results of post-traumatic metacarpal hand reconstruction with microvascular toe transfers

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THE FUNCTIONAL RESULTS OF POST-TRAUMATIC METACARPAL HAND RECONSTRUCTION WITH MICROVASCULAR TOE TRANSFERS

T. KOTKANSALO, S. K. VILKKI and P. ELO
From the Tampere University Hospital, Department of Hand and Microsurgery, Tampere, Finland

The aim of this retrospective study was to evaluate the functional results of grip reconstruction after metacarpal amputation with microvascular toe transfer or transfers. The Sollerman hand function test and modified Tamai score were determined. Additionally, secondary objective outcomes were measured. As subjective outcomes, the patients were asked about pain, satisfaction, sensibility and activities of daily living (ADL). Complications and secondary operations were also recorded. An average of 12 years 5 months (range 11–270 months) follow-up of 8 patients (11 transfers) is presented. Sollerman hand function test averaged 54, range 36–73. The modified Tamai score averaged 63, range 54–70. All except one patient were either satisfied or highly satisfied. Patients’ perception of function in terms of ADL was generally good (average 26 out of 44) with many activities causing no difficulty or only slight difficulty. The study showed that it is possible to reconstruct a reasonable grip using microvascular toe transfers.

Keywords: grip reconstruction, follow-up study, reconstructive microsurgery, Sollerman hand function test

INTRODUCTION

The metacarpal hand may be either congenital or traumatic in origin. The term metacarpal hand was introduced by Michon (Michon and Dolich, 1974). He defined the metacarpal hand as either a complete loss of all the digits or a hand with entirely or partially intact thumb, ‘thumb without fingers’.

In 1997, Wei et al. (1997) proposed a classification of, and guidelines for, the treatment of metacarpal hand (Fig 1A). The classification consists of two main categories determined by the condition of the thumb. In 1999 the same authors proposed guidelines for the treatment of bilateral metacarpal hand (Tan et al., 1999). Their idea was to reconstruct a tripod pinch for the dominant hand and a pulp to pulp pinch for the non-dominant hand in type 2 metacarpal hand. A maximum of five toes were used in these transfers to avoid donor-site complications. The dominant hand was to be reconstructed as the first operation where thenar function was considered adequate.

A classification for the no-finger hand was proposed by Vilkki (2001) (Fig 1B). Level A refers to ‘basic hand’ where at least two functioning digital metacarpophalangeal (MCP) joints exist and the level of thumb amputation is at the distal part of the metacarpal bone or at MCP joint level. This level of amputation has good functional potential because there is no need to use metatarsophalangeal (MTP) joint in reconstruction, thus making the reconstruction of a sound pinch or grip function easier. Level B is a true metacarpal hand with only a functional first metacarpal stump as a movable component. The Vilkki classification B includes both 2B and 2C of the Wei classification and can therefore be divided further into B1 with and B2 without adequate thenar musculature. The condition of the adductor muscle is of special importance in evaluating the thenar muscles because other thenar functions are easier to reconstruct with tendon transfers. Level C is a transcarpal amputation and level D is a more proximal wrist level or distal antebrachial amputation.

The true metacarpal hand poses a challenge for the reconstructive surgeon. If left untreated, the hand has no useful prehension and can be used only to push and press objects. A typical injury is such that it leaves poor quality skin over the distal stump in many cases. The vessels and nerves needed for later reconstruction may be injured far proximally. Tendon-muscle units which could be used to motorise the transfers are sparse and, with delay, will become contracted. The purpose of this study was to assess the functional results of metacarpal hand reconstruction with microvascular toe transfers.

PATIENTS AND METHODS

There were 12 post-traumatic patients with metacarpal type amputations (Fig 2). Preoperatively none of the patients had the ability to grip an object nor did they have a functioning thumb. A total of fifteen toes were transferred in fourteen operations to these patients. All operations were conducted by the second author in a 23-year period starting from March 1982. The patients were all men between 17–60 (average 26) years of age.
No congenital metacarpal hand cases were included in the study. Of the six work-related injuries, five were workman’s compensation cases.

Of the 12 patients included in the study, four had already died, after the operation and prior to the start of the study. The causes of deaths were not related to the operation or the hand injury. A questionnaire was sent to eight patients (11 transfers). An informed consent was received and a clinical follow-up study was undertaken by an observer, the first author, who was not related to the care of the patients.

This study has been approved by the Ethical Committee of Pirkanmaa Hospital District.

Injuries and primary operations

The method of amputation is depicted in Table 1. The amputation in patient 10 was caused by a combined crush and burn injury. This particular case had an associated CRPS. The amputation was unilateral in all cases. There were six right hand and six left hand injuries. Of the nine patients we have adequate information about, only two patients, numbers 4 and 10, had a dominant hand injury.

Replantation had only been attempted in patient 3. In other patients, the primary treatment was revision and coverage of the stump. Patient 5 was injured in 1970, in an era before microvascular toe transfers had started in Finland. For the first reconstructive procedure, he had the distal half of the second metacarpal pollicised and, in a second operation, a syndactyly release and a tendon transfer to enhance first ray adduction, and third ray abduction was performed. There was an average 29 (4–191) months interval from injury to reconstruction.

Classifications according to the extent of the injury

The level of amputation and remaining thumb intrinsic function are important predictors of achievable function. In this series, only patient 2 had two functioning finger MCP joints (Fig 3). According to the no-finger hand classification proposed by Vilkki, there were one level A, 7 level B and the rest level C amputations. All the patients had a thumb injury. The extent of injury and the reconstruction used are illustrated in Fig 2. Even though patients 5, 6, 10 and 12 had some metacarpal bone left or even the MCP joint still intact, they had no functioning thenar muscles. Therefore, according to the classification by Wei, there were four patients in each class IIB, IIC and IID.

Operations and rehabilitation

The fourteen operations lasted on average 10 hours, ranging between 7 to 12 hours per operation. The operations were most often done with one surgical team. In fact, only in the last two patients was there a separate team to harvest the toe.

Toe flap elevation and transfer

A single second toe was transferred in 9 of the 12 patients (Fig 2). The first toe was used for patient 1. Patient 10 had first the contralateral second toe transferred to
Fig 2 The patients are arranged according to the Vilkki classification. Transferred toes illustrated in grey colour. In patient 8 the opposing post was a non-vascularised bone graft (dark grey). The Wei classification also illustrated with each patient. Bi = adequate thenar function; B2 = inadequate thenar function; R = right; L = left; N-d = non-dominant; D = dominant.
reconstruct the thumb and, in the second operation 16 months later, the ipsilateral second toe transferred to reconstruct the little finger. Patient 12 had a simultaneous transfer of second and third toes to the position of middle and ring finger and, in the second operation 20 months later, a transfer of the second toe to the position of the thumb. The single toe transfer was placed in thumb position in all the patients except patient 4. He had the transfer placed in fifth ray position because it was the only one with an intact CMC joint.

The method of raising the toe flap has been previously detailed by the senior author (Vilkki and Kotkansalo, 2007). The position and length of the transfer has to be such that a firm pinch is possible with the

<table>
<thead>
<tr>
<th>Patient number</th>
<th>Age at injury</th>
<th>Injury type</th>
<th>Interval to reconstruction (months)</th>
<th>Recipient artery</th>
<th>Donor artery</th>
<th>Number of nerves reconstructed</th>
<th>Number of tendons reconstructed</th>
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<tr>
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<td>64</td>
<td>1-2 PMTA</td>
<td>2</td>
<td>4</td>
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<td></td>
<td></td>
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</tbody>
</table>

Average 26 29

Artery used for reconstruction: DMTA = dorsal metatarsal artery; PMTA = plantar metatarsal artery.
Donor artery: 1 = dorsal branch of radial; 2 = common digital; 3 = radial; 4 = deep/superficial arcus; 5 = volar digital; 6 = princeps pollicis.
opposing surface. The MTP joint was included in the transfer in 12 of the 15 transferred toes. Since a single toe was used for reconstruction in most of the cases, the transfer was placed so that it would enable a pinch grip with the stump. In patient 10 a pulp-to-pulp pinch was reconstructed with two separate transfers and in patient 12 a tripod pinch was reconstructed in two stages using a double toe and a single second toe.

Osteosynthesis was achieved with a single or double K-wire and a loop of cerclage wire. The reconstructed ray had an intact CMC joint in all except patients 7, 8 and 9 in whom the second metatarsal was connected to the trapezium (Fig 4). Patient 8 had superfluous unstable soft tissue coverage on the opposing stump side and this was stabilised and reconstructed using a free iliac-crest bone graft.

The transferred second toe with three joints has a tendency to claw. To prevent that while achieving stability and retaining the potential for abduction and adduction at the MTPJ level, the tendinous parts of the intrinsic tendons were harvested with the transfer and then activated in the reconstructive phase of the operation. The intrinsic tendons of the toe have a similar course and function as in a finger. They produce MTP joint flexion and IP joint extension. The intrinsics are situated laterally and medially to the long axis of the toe, acting to produce abduction and adduction of the toe at MTPJ level. Activating the intrinsic tendons on both sides of the MTP joint enhances the dynamic stability. This also synchronises the active flexion of the transferred toe. In this way, the tip of the transferred toe does not flex too early and there is optimal positioning for the pulp during opposition. In this series, the number of tendons reconstructed varied between two and seven for each toe (Table 1). The intrinsic tendons were reconstructed in ten out of fourteen operations. A more detailed scheme of tendon reconstruction was presented by Vilkki in 2007 (Vilkki and Kotkansalo, 2007).

In most cases, a single artery was reconstructed (Table 1). Only with patients 9, 12 (first operation) and 10 (second operation) were two arteries reconstructed. Most often, the 1-2 dorsal metatarsal artery (I/II DMTA) of the transfer was used, and the recipient artery was the dorsal branch of the radial artery. Only one vein was reconstructed in all transfers, except for patient 11. A broad veno-subcutaneous flap was harvested with the vein (del Pinal et al., 2005, Vilkki, 1995). This flap is useful in covering vascular anastomoses, neurorraphies and tenorraphies especially in cases with limited dorsal skin on the hand. The flap can be safely covered with a split thickness skin graft.

Adequate sensibility is a prerequisite for a good function of the toe transfer. That is why as many nerves as possible were reconstructed to the transfer. In nine operations, one or two of the dorsal nerves were also reconnected (Table 1). In our opinion, the dorsal nerves may contribute to proprioception of the toe transfer and hence facilitate the use of the transfer. Trophic changes in the transfer may be avoided by including multiple nerve repairs.

A split thickness skin graft was necessary as part of the final coverage of the recipient site in all of the cases. Additionally, a hemi-pulp flap from the big toe was harvested in cases where the skin quality of the opposing surface for the transfer was considered inadequate or when there was a need for augmentation at the web area. This was done with patients 6, 7, 10 and 12.

Postoperative care and rehabilitation

The follow-up of microvascular transfers was carried out in a normal hand and microsurgical ward after the first 12–24 hours in the recovery unit.

All the patients used a protective dynamic splint in the hand for about 1–2 months. Rubber bands were used to create a pull on predetermined sections of the transplant. This was done in order to enhance extension of the IP joints and the flexion of the MTP joints. The purpose of the extension force was to protect the complicated extensor and intrinsic tendon system and thus prevent
later extension lag. About a week postoperatively, cautious active motion was started.

Care of the donor site

The donor site, especially the web area between the first and third toes, was designed to be closed without tension or skin graft. This is considered an important technical feature to prevent problems such as wound healing delay or painful contracted secondary scar on the foot. It is better to use a skin graft in the recipient than the donor site.

The donor foot was protected with a walking plaster cast for about one month to facilitate wound healing. Weight bearing was allowed and encouraged 1 week postoperatively.

Study protocol

Two questionnaires were used. The first questionnaire, sent to patients, was divided into sections concentrating on activities of daily living (ADL), problems of the transfer, cosmetic aspects, satisfaction with the operation and occupational status according to the Tamai score (Tamai et al., 1983). The original Tamai score was translated into Finnish, the ADL section was modified so that the patients could answer on a scale of six instead of three, and the questions in the second section concerning the replant were converted to questions about the toe transfer.

The second questionnaire, designed specifically for toe transfer patients, was filled out at the clinical follow-up visit. This questionnaire consists of questions about pain, sensibility, satisfaction, social acceptance, cosmetics and ADL. The questionnaire has 19 questions of which 11 focused on ADL. These questions are either generalised (e.g. handling oneself dressing up or washing up) or task and hand-oriented (e.g. strong gripping, handling coins, key pinch). Patients were asked to rate their answers into four categories that equalled one to four points. No complaint gave four points, minor complaint gave three points, moderate complaint gave two points and major complaint gave one point. From the ADL section of the questionnaire a score ranging from 11 to 44 points was calculated. The more points the better the result. The cosmetic appearance was of specific interest, so the patients were asked to rate their satisfaction about the outlook of the transferred toe in a visual analogical scale (VAS) expressed as a percentage. In addition, patients were asked about the symptoms and function of the donor foot.

The Sollerman hand function test was used as a primary objective outcome measure (Sollerman and Ejeskär, 1995). It has 20 tasks measuring different forms of grip. Most of the tasks are done single-handed and when both hands are used the other hand has a clearly defined assistant role. Both hands are tested. Each task is evaluated on the following scale of performing: without difficulty (in 20 seconds); with slight difficulty (20–40 seconds); with great difficulty (40–60 seconds); incomplete performance (within 60 seconds) and not performing at all. Points are given from 0 to 4 for every task so the result varies between 0 and 80 points. A normal dominant hand should get 80 points and non-dominant hand 77–80 points.

The modified Tamai score was also used to evaluate the function of the hand after toe transfer (Tamai et al., 1983). The Tamai score was designed to assess hand function after thumb or finger replantation. It consists of a questionnaire and a clinical examination. The questionnaire part was sent to patients to be filled out beforehand. The clinical examination gives points for movement and sensibility. In the Tamai score, the points for movement of the thumb replant are divided between total range of motion and opposition. In contrast, the points for the finger replants are given only for total range of motion. Sensibility was evaluated according to criteria set by the British Medical Research Council. Points range from −10 to 100. Ten points can be deducted in case of inability to work because of the injury.

Strength, sensibility and movement were measured as secondary objective outcome measures. The strength was measured as key pinch of both hands and grip strength (Jamar dynamometer) of the uninjured hand. The reported value for strength is the better of two consecutive attempts. Sensibility was measured with Semmes-Weinstein filaments, both static (s2PD) and moving (m2PD) two-point discrimination and a distinction between sharp and dull touch. Sensibility was measured from the pulp of each of the toe transfers and from the thumb of the uninjured hand. The second or third toe transfers have small distal and intermediate phalanges such that it is difficult to measure reliably the movement and position of the distal interphalangeal joint. So, the DIP and PIP joints were considered as one IP joint. A goniometer was used to measure both the active flexion and the extension lag of all the toe transfers and the uninjured thumb. Movement was measured from the IP and the MCP (MTP when present) joints.

The opening of the web during maximal extension between the transfer and the stump or between two opposing transfers was measured. This was done by measuring with a ruler the distance between the edge of the nail of the transfer and the opposing surface, whether it was the stump or the other transferred toe. Moreover, the patients were asked to grasp as large a diameter cylinder as possible. Both of these measurements were done for the uninjured hand also. These tests measured the opening ability of the newly created web. In order to assess how well the transfer approximated to the opposing surface, the patients were asked to hold a sheet of A4 paper.
During the follow-up visit, radiographs were taken from hands, all transfers and their counterparts in the other, uninjured hand. Further, radiographs were taken of both feet with the patient standing and lying down. The length of the donor toe, the angle of osteosynthesis and the extension deficit between the distal phalanx and metatarsal or metacarpal was measured. In addition, signs of osteoarthritis or osteopenia were recorded. Hallux valgus and osteoarthritis were evaluated from the foot radiographs. All radiographs were assessed by a radiologist not related to the care of the patients, the third author.

RESULTS

A follow-up of an average 149 months (12 years 5 months), range 11–270 months, of the eight surviving patients (11 transferred toes) that were examined according to the study protocol is presented. Individual follow-up times are presented in Table 2.

Primary outcomes

Our ADL score, designed for toe transfer patients, averaged 26 (range 24–34) out of a maximum of 44 (Table 2). The score for the Sollerman hand function test averaged 54 (range 36–73) for the injured hand and 79 (76–80) for the uninjured hand (Table 2). The reconstructed hand scored especially well in picking up objects from a flat surface, opening and closing a zipper, lifting a 3 kg weight from a handle, using a screwdriver, pouring water from a pitcher and from a cup. In those tasks, the function was rated on average as normal or slightly diminished (3.1–4 points). On the other hand, picking up coins from a wallet, closing buttons and pouring water from a carton were more difficult and patients were totally or partially incapable of performing these tasks (0.8–1.3 points).

The modified Tamai score is reported only for patients 3, 5, 8, 9 and 11 because they had a single toe transferred to the thumb position (Table 2). The modified Tamai score averaged 63 points (54–70 points) which would equal good according to the original article by Tamai (Tamai et al., 1983). The ADL section of the modified Tamai questionnaire has twenty questions each yielding 0–1 points. The patients in this study averaged 7.25 points (range 4.75–9.5 points).

Secondary outcomes: objective

Key pinch was measured from seven patients and patient 10 pinched between the pulps of the two transferred toes. The average key pinch was 4.4 kg (9.7 pounds), range 2–7 kg and that was an average of 41% of the uninjured hand (Table 3). Grip strength was measured only from the uninjured hand. It averaged 44 kg (97 pounds), range 22–58 kg. Patient 8 had a poor grip because of non-injury-related both cervical spine and carpal tunnel compression.

S2PD was ≤ 10 mm in only two of the 11 transfers tested (Table 3). Additionally, m2PD was ≤ 10 mm in patient 9. Three transferred toes recognised the f3.61 filament, two recognised k4.56 filament and the rest recognised j4.31 filament of the Semmes–Weinstein test. All could differentiate between sharp and blunt touch, with the exception of patient 10.

There was considerable variation in the active movement on IP joints (Table 3). The average active

<table>
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<tr>
<th>Patient number</th>
<th>Sollerman: transplant</th>
<th>Sollerman: control</th>
<th>Modified Tamai score</th>
<th>Modified Tamai ADL</th>
<th>Our ADL</th>
<th>Return to work</th>
<th>Follow-up of transferred toes (months)</th>
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</table>

Patients 1, 2, 6 and 7 did not attend follow-up.

1Dominant hand injury.

2Modified Tamai score not reported.
movement was 49° and range 10–125°. The average of IP joint movement for transfers in thumb position compared to the uninjured thumb IP joint movement was 52%. Total range of active motion (TAM) was calculated by adding together the active movement of the IP and MTP joints. TAM averaged 83° ranging between 10–185°. TAM for transfers in thumb position averaged 90°, which was 79% of the movement of the control thumb in the uninjured hand. The active flexion of a transferred MTP joint was 27° ranging from 0–90° and the average extension lag was 17°.

In maximal extension, the distance between the edge of the nail of the transferred toe and the opposing surface was on average 53 mm, ranging between 13 and 90 mm. The average cylinder grip was 4.6 cm (Fig 5). Patient 5 was not able to actively grasp a cylinder because of poor active web opening. All the patients were able to hold a size A4 paper sheet thus making the range and direction of motion adequate for pinching function.

Secondary outcomes: subjective

In general, pain (whether at rest or during use), poor sensibility or hyperaesthesia were not considered a problem. In our questionnaire, they averaged 2.9–3.8 points. Patient 10 was an exception reporting pain during use and poor sensibility to be a major complaint. Cold sensitivity on the other hand was a major complaint for patients 3, 5 and 10. The average points for cold sensitivity were 1.8.

The patients' satisfaction with the operation was assessed in the two questionnaires in a slightly different way. According to the modified Tamai score, half of the patients were either highly or fairly satisfied. Only patient 10 was so dissatisfied that they, in retrospect, would not have selected the operation again. In the other questionnaire the patients were asked to rate their satisfaction in four categories. Patients 3 and 10 reported minor and major dissatisfaction with the operation, respectively. All others were satisfied with their operation.

Satisfaction with the cosmetic outcome averaged 2.8 points. Patients 3 and 10 had a major complaint with the appearance of the reconstructed hand. Moreover, the satisfaction of the cosmetic appearance of the transferred toe or toes measured with a VAS averaged 61, range 16–96, where 0 was the lowest and 100 was the highest value on the scale. Social acceptance averaged 3.4 points. Patients 3 and 11 had returned to the same work as before the accident. The rest had either re-education or lighter work.

Radiological outcomes

To adjust the gripping function individually, the metatarsal bone was fixed into a variable degree of flexion depending on the status of the rest of the hand. The angle at the osteosynthesis site was measured from lateral radiograph and averaged 51°, range 26–77, in patients with MTP joint included in the transfer. The length of the first ray was measured from the distal cortex of scaphoid to the tip of the distal bone. For the reconstructed ray, this averaged 88 mm, range
66–99, and for the contralateral ray 113 mm, range 107–117.

In order to evaluate the degree of shortening caused by extension lag and angle at the osteosynthesis site together, the length of each bone of the reconstructed first ray was measured, summed up and compared with the length measured as described above. Length measured this way summed up to an average of 104 mm, range 94–118, which resembles the length of the contralateral ray. The proportional shortening averaged 1.17, range 1–1.4. Neither the length of the ray nor the proportional shortening was related to the Sollerman scores.

Osteopenia of the reconstructed hand could be seen in all except patient 9. This patient received the highest scores in the Sollerman test and the modified Tamai score. He was also able to return to his previous work. Thus, the normal bone structure may be due to ability to use the hand somewhat normally. Moderate arthritis in the base of the first ray was seen in three out of nine cases (33%).

Complications and secondary operations

There was one failure in this series (Table 4). The vascular failure in patient 6 was due to a postoperative infection. Two revisions and lavages were not able to save the transfer, and in a fourth operation the transferred toe was removed. Patient 7 was taken back to the operating theatre just four and a half hours after the completion of reconstruction to remove a haematoma and add two sutures to the arterial anastomoses. The temperature of the transfer decreased in patient 5 and required removal of skin sutures and a haematoma from the wound. That was done in the ward. The transferred toes of patients 7 and 5 healed uneventfully from then on. Patient 8 had problems with healing of the recipient and the donor site wound, both requiring skin transfers. The foot wound of patient 12 needed a revision and skin grafting after the first operation where a block of second and third toes were harvested.

There were two secondary operations (Table 4). Patient 5 had an extensor tendon tenolysis 9 months after the reconstruction without any improvement of motion. Patient 10 had an arthrodesis of the DIP joint of the transfer and a shortening of third metacarpal 3 years after reconstruction. The arthrodesis was done because of a flexion contracture and the metacarpal was shortened to widen the first web.

In total, half of the patients needed a subsequent operation after the reconstruction. There were eight hand and two foot operations. Patient 6 needed three re-operations.
DISCUSSION

Literature review identified 14 previous articles presenting patients with metacarpal amputations reconstructed using microvascular toe transfers (Table 5). The perspective in these articles was not the same as in ours, so the results may not be comparable. In the studies mentioned, the follow-up periods ranged from not reported to 288 months. Some articles presented only bilateral cases (Tan et al., 1999; Wei et al., 1999), while some incorporate also finger and thumb reconstructions in the presented material. In most articles, some secondary outcome measures were presented. Only two articles showed any measurements of function (Chung and Kotsis, 2002; Williamson et al., 2001). The function of the reconstructed hand is difficult to measure. Movement, sensibility and force of the transferred toe or toes all contribute to the function, but reflect only one aspect of it.

In our study the function of the reconstructed hand was evaluated with both subjective and objective tests. Our ADL questionnaire showed moderately good results with most patients receiving similar results. Patients reported better results in two-handed than in single-handed tasks. Only patients 4 and 10 had a dominant hand injury and this most likely influenced the results in these particular cases. Also, the ADL section of the modified Tamai score showed little variation between the patients. The Sollerman hand function test averaged 54 in our patients. There was a considerable variation in results between different tasks and patients. Eleven of the 20 tasks averaged three or more points which mean that they were performed with slight difficulty (within 40 seconds) or without difficulties. Even tasks requiring small instrument manipulation, like picking up a key and turning it in a slot; closing and opening a zipper or picking up paper clips from a flat surface and placing them into an envelope were completed with on average only slight difficulties. The two articles presenting measurements of function used the Jebesen–Taylor test. Therefore their results are not comparable with ours.

S2PD, m2PD, Semmes–Weinstein filament test and distinction between sharp and dull touch were used to measure sensibility of the transferred toes. The first two tests are difficult to perform reliably and reproducibly. That is why exact values are not reported, but a distinction is made between $\leq 10$ mm and $\geq 10$ mm. The recovery of sensibility was not good in our patients. Only patients 4 and 8 reported $s2 PD \leq 10$ mm. Nevertheless, only patients 3 and 10 reported poor sensibility to be a moderate and a major complaint, respectively. Reported sensibility in other articles varies markedly. The reason may be either difference in technique of nerve reconstruction, follow-up time or in methods of measuring the sensibility. In the largest series, Yu and Huang (2000) reported $s2PD < 10$ mm in all 58 patients and Lister (Lister et al., 1983) reported $s2PD < 10$ mm in 75% of patients with over 2 years follow-up. The results of the sensory recovery seem to be better in other authors’ series compared to our own.

Wei et al. (1989) reported an average of 50° of motion for the transferred MTP joint and 35° for the composite MTP joint reconstruction. In our patients, the average motion for the transferred MTP joint was 27° (range 0–60) with an extension lag of 17° (range 10–90). In Table 5, the reported IP joint movement ranges

---

### Table 4—Complications and secondary operations

<table>
<thead>
<tr>
<th>Patient number</th>
<th>Complications</th>
<th>Flap survival</th>
<th>Hand</th>
<th>Foot</th>
<th>The complication or the type of secondary operation performed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No</td>
<td>Yes</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>No</td>
<td>Yes</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>Yes</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>No</td>
<td>Yes</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Hand</td>
<td>Yes</td>
<td>1</td>
<td>0</td>
<td>Removal of haematoma in the ward after transfer temperature drop. Extensor tenolysis</td>
</tr>
<tr>
<td>6</td>
<td>Hand</td>
<td>No</td>
<td>3</td>
<td>0</td>
<td>Two revisions and lavages because of purulent infection. Amputation of the necrosed transfer and drainage</td>
</tr>
<tr>
<td>7</td>
<td>Hand</td>
<td>Yes</td>
<td>1</td>
<td>0</td>
<td>Removal of haematoma and two patch sutures to arterial anastomoses 4 h 30 min after completion of reconstruction</td>
</tr>
<tr>
<td>8</td>
<td>Hand/Foot</td>
<td>Yes</td>
<td>1</td>
<td>1</td>
<td>Revision of both donor and recipient site wounds and skin transplantation</td>
</tr>
<tr>
<td>9</td>
<td>No</td>
<td>Yes</td>
<td>0</td>
<td>0</td>
<td>Arthrodesis of the transferred DIP joint and resection of III metacarpal</td>
</tr>
<tr>
<td>10</td>
<td>No</td>
<td>Yes</td>
<td>2</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>No</td>
<td>Yes</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Foot</td>
<td>Yes</td>
<td>0</td>
<td>1</td>
<td>Revision and skin transplantation of donor wound</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>8</strong></td>
<td><strong>2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
between 25–116°. In our patients, the average motion of the IP joint was 44° (range 10–125) with an extension lag of 42° (range 0–80). The range of motion of the transferred MTP joints seems to be little less and of the IP joints quite the average in our patients when compared to the other studies as presented in Table 5. The intrinsic reconstruction that we used may limit the motion of the transferred MTP joint but at the same time directs that range of motion to a more functional arc.

The significance of the level of the injury was evaluated by using the primary outcome measures as end points. The Vilkki classification, the Wei classification or the ability to oppose with the reconstructed thumb did not seem to correlate with the result according to primary outcome measures. Interestingly, patients with Vilkki classification C seemed to be more satisfied with the operation than class B patients (modified Tamai questionnaire 16.25 versus 8.75, respectively). In the Sollerman hand function test the best and the worst results were scored by patients in the Vilkki classification C, patients 8 and 9 respectively. Our comment about the data regarding injury level is as follows: firstly, the patient series is too small to detect the influence of the level of the injury to the primary end point measures and secondly, there are most likely factors we cannot measure, like patient motivation, that influence the results. Additionally, the injured hand dominance did not correlate with results in primary outcome measures.

In our study population, the number of toes transferred for each patient varied from one to three. For patients 10 and 12, two and three toes, respectively, were transferred. For the rest, a single second toe was transferred in a thumb position, except for patient 4 where the toe was placed in a little finger position. In all articles presented in Table 5 (except for Lister et al. (1983) where the information is not available) the goal has been to reconstruct a hand with a thumb and one or two digits. In our series, single second toe transfer patients scored better than multiple toe transfer patients in the Sollerman hand function test (average 57 versus 44), the ADL section of the modified Tamai score (average 7.7 versus 5.8) and in our own ADL score (27 versus 24). Despite the results, it is impossible to conclude that single toe transfer is better than multiple toe transfers. Our results may be influenced by a selection bias and because of a small sample size they do not reach statistical significance.

A similar study protocol was used by Vilkki and Kotkansalo (2007) in 13 patients with wrist level amputations. In those patients, a pinch grip was reconstructed with a single second toe transfer placed in radial/volar aspect of distal radius. The current

### Table 5—Previous studies

<table>
<thead>
<tr>
<th>Study</th>
<th>Number of patients (MC-hand)</th>
<th>Average follow-up (months)</th>
<th>MTP joint</th>
<th>IP joints</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>O’Brien et al. (1978)</td>
<td>2 (2)</td>
<td>21, 24</td>
<td>45</td>
<td>30</td>
<td>‘well worthwhile’</td>
</tr>
<tr>
<td>Tsai et al. (1981)</td>
<td>8 (8)</td>
<td>19 (4–43)</td>
<td>14/36</td>
<td>37/90</td>
<td>‘most rewarding’</td>
</tr>
<tr>
<td>Holle et al. (1982)</td>
<td>2 (1)</td>
<td>12</td>
<td>—</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Lister et al. (1983)</td>
<td>54 (12)</td>
<td>21 (5–72)</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Gordon et al. (1985)</td>
<td>16 (7)</td>
<td>29 (7–45)</td>
<td>50 (0–150)</td>
<td>60 (80–148)</td>
<td></td>
</tr>
<tr>
<td>Wei et al. (1989)</td>
<td>25 (10)</td>
<td>60 (24–108)</td>
<td>52 (30–80)</td>
<td>45 (all patients)</td>
<td>‘excellent option’</td>
</tr>
<tr>
<td>Strauch et al. (1993)</td>
<td>4 (3)</td>
<td>69 (57–92)</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Tan et al. (1999)</td>
<td>3 (3)</td>
<td>57 (44–70)</td>
<td>?</td>
<td>?</td>
<td>‘all regained prehensile ability’</td>
</tr>
<tr>
<td>Yu and Huang (2000)</td>
<td>58 (58)</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>‘92.2% of patients recovered hand function’</td>
</tr>
<tr>
<td>Williamson et al. (2001)</td>
<td>8 (3)</td>
<td>45 (11–144)</td>
<td>59 (two joints)</td>
<td>28 (all patients)</td>
<td>Jebsen–Taylor: ‘below normal with few exceptions’</td>
</tr>
<tr>
<td>Gülünönen and Gudemez (2006)</td>
<td>5 (3)</td>
<td>288 (264–312)</td>
<td>41 (2 cases, 5 transplants)</td>
<td>116 (2 cases, 5 transplants)</td>
<td>?</td>
</tr>
<tr>
<td>Fan et al. (2007)</td>
<td>2 (2)</td>
<td>18, 24</td>
<td>?</td>
<td>?</td>
<td>case 1: ‘nimble and forceful opposition action’</td>
</tr>
<tr>
<td>Present study 2</td>
<td>12 (12)</td>
<td>134 (11–257)</td>
<td>27 (0–60)</td>
<td>44 (10–125)</td>
<td>Sollerman 54 (36–73)</td>
</tr>
</tbody>
</table>

For movement the results of first toe transfers are excluded. Average (range) values are reported for follow-up, motion and function.

1The values presented for movement also include transfers for other than metacarpal hand reconstruction.

2Results of follow-up, motion and function from eight patients participating in follow-up.
Patient series differs from that published in 2007 in that these patients have a sensate and moving palm. The wrist flexors and extensors were intact, enabling wrist movement and tenodesis movement of the toe transfer. In spite of this, there was no significant difference in both the modified Tamai ADL and our own ADL scores when comparing the wrist and metacarpal level amputation patients. In addition, the results of secondary objective and subjective outcome measures showed no great difference. On the other hand, the Sollerman hand function test averaged better in the metacarpal hand patients when compared to antebrachial stump patients; 54 versus 36, respectively.

The weakness of this study is the small number of patients. There were four patients out of 12 who were not available for formal review (deceased from unrelated causes). With this in mind, even the most logical predictions like ‘the more proximal the injury, the worse the result’ cannot be verified. This study also bears the flaws of retrospective studies. The information

Fig 6 Good motion (A and B) and function (C and D) shown in patient 4.
concerning the pre-study time is not complete. Thus, functional comparison with the preoperative situation is purely subjective.

There is a considerable difference in our case series when compared to what is presented in other articles, listed in Table 5, in the ideology of treatment. The senior author has been extremely careful not to cause any harm to the donor site. Our patient cases were not amenable to the use of multiple toe transfers. Cold intolerance in the donor site may be more of a concern in the Nordic environment.

The patient numbers are too small to detect significant differences within the group. In addition, comparison of functional results between our cases and similar patients reported by others is limited by the small number of patients included and the different outcome measures used. It would be logical to assume that the level of injury, the method of amputation or the number of digits reconstructed would influence the functional outcome. This, however, cannot be verified in our study. We can only conclude that an adequate function with high patient satisfaction can be achieved even with single toe transfer in these non-functional post-traumatic situations (Fig 6).

Patient 10 scored lowest in almost all categories. He had severe post-traumatic neuropathic pain, possibly due to the deep grade 3 burn injury. His reconstructed hand was clearly put into practical use, but the pain problem made him dissatisfied. Difficult neuropathic pain must be taken into consideration when planning toe to hand reconstruction. Both the patient and the surgical team must remember that the results of the toe transfer surgery may not always be pleasing. With adequate and careful surgical planning, satisfaction is achievable with single toe transfer. Fortunately, nowadays the need for these post-traumatic reconstructions seems to be less frequent with development and availability of primary replantation surgery.

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References


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Tero Kotkansalo, Turku University Hospital, PL 52, 20521 Turku, Finland. Tel.: +358-2-3130000; fax: +358-2-3133276; E-mail: tero.kotkansalo@tyks.fi.

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Long-term functional results of microvascular toe-to-thumb reconstruction

T. Kotkansalo, S. Vilkki, P. Elo and T. Luukkaala

From the Department of Hand and Microsurgery, Tampere University Hospital, Tampere, Finland, Department of Radiology, Regional Imaging Centre, Tampere, Finland; Department of Biostatistics, Tampere University, Tampere, Finland

Abstract

The purpose of this study was to evaluate the long-term functional results of microvascular toe-to-thumb reconstruction after trauma. Forty-one patients meeting the inclusion criteria were available for a clinical follow-up study. The function of the hand was assessed with questionnaires as well as with modified Tamai and Sollerman hand function tests. According to the questionnaires, most activities were considered easy or quite easy and the majority of the patients (36/41) managed with no or minor complaints. Clinical tests showed good recovery of function. Patient satisfaction was high. There were superficial infections in five hands and in six donor feet. In total, 16 late corrective operations were done to eight patients. Microvascular toe transfer is a good option for grip reconstruction after thumb amputation. The extent of the initial injury influences the achievable outcome, yet even a single toe transfer can restore adequate grip function.

Keywords

Grip reconstruction, microsurgery, outcome study, second-toe transfer, Sollerman hand function test, thumb amputation

Introduction

The thumb plays a key role in the function of the hand. It participates in almost all forms of grip. Hence, the loss of the thumb severely reduces the pinching and gripping ability of the hand. It has been estimated that the thumb contributes to 40–50% of the function of the hand (Strickland and Kleinmann, 1993).

The study by Chung and Wei (2000) showed that toe transfer patients scored statistically significantly better in overall hand function, activities of daily living (ADL), work performance, aesthetics and satisfaction when compared to patients who had refused a thumb reconstruction. There have been a few similar studies attempting to assess the function of the hand after microvascular thumb reconstruction with questionnaires or tests (Doi et al., 1985; Fan et al., 2006; Frykman et al., 1986; Leung, 1983; Michon et al., 1984; Poppen et al., 1983; Wilson et al., 1984). The purpose of our study was to evaluate the long-term functional results of microvascular toe-to-thumb reconstruction after trauma. To the authors’ knowledge this is the first study of a group of similar patients (i.e. only thumb reconstructions) with long-term follow-up that has been studied with tests that measure function both subjectively and objectively. Long-term is defined as over 3 years, since by this time neural recovery is complete and most of the adaptation to the newly reconstructed thumb has occurred.

Patients and methods

In total, we could identify 52 patients with microvascular thumb reconstruction. Forty-nine of those had traumatic thumb amputations and three had surgical thumb amputations to treat various conditions. No patients with congenital thumb aplasias were included. Three of the 52 patients had died by the time of this study. A questionnaire was sent to the remaining 49 patients. Forty-one of those returned our questionnaire with an informed consent. The patient demographics are presented in Table 1.
Injuries

All the 41 patients had a thumb amputation proximal to the interphalangeal (IP) joint with at least some length and function in a finger to act as a counterpart for the transfer. The information about the extent and the method of amputation is presented in Table 1. Three of the patients had bilateral amputations.

Study protocol

A similar study protocol has been used by the authors and is described in detail in previous articles (Kotkansalo et al., 2009; Vilkki and Kotkansalo, 2007). An observer who did not participate in the care of the patients carried out a clinical follow-up of these patients.

The first questionnaire, modified from the one recommended by the International Federation of Societies for Surgery of the Hand (IFFSH) Subcommittee on Replantation (Tamai et al., 1983), was sent to patients. This questionnaire was used because our patient group approximated to that of the original publication. The second questionnaire (Kotkansalo et al., 2009), designed by the authors for the toe transfer patients, was filled out at the clinical follow-up visit.

The Sollerman hand function test was used to measure function objectively (Sollerman and Ejeskär, 1995). This test was chosen because it evaluates both the time consumed and, more importantly, the quality of grip used for completing each task. The test also includes bimanual tasks, but the other hand has a distinct assistant role and the function of the tested hand can be evaluated individually. In addition, the score by the IFFSH Subcommittee on Replantation for thumb replantation patients (the Tamai score) was used in this study (Tamai et al., 1983).

Movement, sensibility and strength were determined as secondary objective outcomes. All the measurements of physical variables were used in the other hand as well. Thus, the other hand acted as a control for patients with unilateral injury.

During the follow-up visit, radiographs of feet, hands and transferred toes as well as contralateral thumbs were taken. The radiographs were assessed for any signs of osteoarthritis (Gahunia et al., 1995) or osteopenia by a radiologist who had not participated in the care of the patients.

Information about complications and secondary operations was collected from patient charts and during follow-up visit.

Table 1. Details of 41 patients

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male/female</td>
<td>33/8</td>
</tr>
<tr>
<td>Age at injury in years, median (range)</td>
<td>23 (2–48)</td>
</tr>
<tr>
<td>Dominant hand injury</td>
<td>23</td>
</tr>
<tr>
<td>Interval to reconstruction in months, median (range)</td>
<td>8 (1–102)</td>
</tr>
</tbody>
</table>

**Number of rays amputated**

- 1 (thumb) 18
- 2 4
- 3 9
- 4 5
- 5 5
- Mean 2.4

**Level of thumb amputation**

- Proximal phalanx 15
- MC (thenar muscles intact) 19
- MC (thenar muscles absent) 5
- Proximal to thumb CMC joint 2

**Type of amputation**

- Crush 15
- Avulsion 12
- Explosion 6
- Other 3
- Circulating saw 2
- Surgical 3

MC: metacarpal bone; CMC: carpometacarpal.

Analysis of data

Differences in categorical variables between different transfer groups were tested by Fisher’s exact test. Due to skewed distributions, continuous variables were expressed as medians and ranges and tested by the Mann–Whitney nonparametric test. Spearman’s correlation ($r$) was used to test associations with the two types of questionnaires about activities of daily living (ADL), the Sollerman hand function test and the modified Tamai score. Logistic regression models with odds ratios and 95% confidence intervals were used to examine the association between age, gender, transfer used, number of nerves reconnected, whether the metatarsophalangeal (MTP) joint was included in the transfer or not and injury patterns with the following: Sollerman hand function score $<70$ ($\geq 70$ means performing without difficulties); modified Tamai score $<60$ ($\geq 60$ means good or excellent result); modified Tamai ADL $<12.5$ ($\geq 12.5$ means easy or quite easy); our ADL $<30$ ($\geq 30$ means no or minor complaint); and with return to work. $P$-values $<0.05$ were considered as statistically significant.
Reconstructive operations

The thumb was reconstructed with a microvascular transfer of the big toe in five patients and with a third toe in one. For the remaining 35 patients, a second toe transfer (Vilkki and Kotkansalo, 2007) was chosen. The MTP joint was included in the reconstruction in eight operations (Figure 1).

Clawing is a well-known adverse consequence when the second toe with three joints is used as a transfer. This issue was addressed with several technical features in the reconstructive phase of the operation (Figure 2). The veno-subcutaneous flap (del Piñal et al., 2005; Vilkki, 1995), routinely harvested with the toe transfer, allows the use of a split thickness skin graft, since it covers the dorsal anastomoses and provides a vascularized gliding surface for structures beneath.

One week postoperatively a dynamic splint was individually applied and gentle active movements were started.

Results

The median follow-up was 187 months (15 years and 7 months) (range 38–358 months), for the 41 patients. The most relevant clinical results are presented in Table 2. The tests used to measure function (modified Tamai ADL, our ADL, the Sollerman hand function test and the modified Tamai score) all correlated well with each other ($r > 0.4$, $P < 0.05$).

Primary outcomes

Eleven of the 20 activities reported in the modified Tamai questionnaire were considered on average easy or quite easy. Sixteen patients had an average of less than 12.5 points, which indicates that the remaining 25 patients could manage the ADL easily or quite easily.

Of the specific questions asked in our ADL questionnaire, only handling small objects had an average of less than 2.5 points, which means that all the
Figure 2. Minimizing extension lag. (A) The second toe transfer has an extensor mechanism resembling that of a finger with three intrinsics. The lumbrical tendon runs plantar to the intermetatarsal ligament. In a transfer with three joints, ideally all intrinsics are reconstructed. (B) The superficial flexor tendon (FDS) is better to provide thumb-like flexion because it attaches to the intermediate phalanx. The combined length of the distal and intermediate phalanges of the toe approximates that of the distal phalanx of the thumb. The FDP is tenodesed to FDS to prevent hyperextension of the distal interphalangeal joint (DIP). The muscle selected to motor the toe IP joint flexion is sutured to FDS tendon. (C) The short and long extensors of the toe are completely separated from each other and then reconstructed with individual motors. Often the short extensor [and lumbrical tendon] gives better extension to the tip. The short extensor tendon is tightened further in relation to the long extensor to achieve better extension of the distal phalanx. (D) A radiograph of a K-wire used for temporary arthrodesis of the DIP joint. The joint is fixed in extension to protect the more delicate extensor and intrinsic tendon repairs and can be removed after 2–3 months.
others were carried out with minor or no complaints. Thirty-six patients scored ≥30 points, which means that they were able to cope with ADL with minor, or no complaints.

The tasks evaluated in the Sollerman hand function test were generally performed without difficulties (within 20 s) (Figure 3). Only using a screwdriver, turning hexagonal nuts and buttoning up were rated on average below 3.5 points. Furthermore, 36 patients scored over 70 points, which indicates that they performed the required tasks without difficulties.

According to the scale set by Tamai et al. (1983), the results of the modified Tamai score were excellent in 18 patients, good in 15, fair in four and poor in three patients. Thus, the results were either good or excellent in 83% of the cases.

Patients with only thumb ray amputation (n = 18) scored better than patients with multiple ray amputations (n = 23) in the modified Tamai ADL. The mean scores were 16 and 12, respectively (odds ratio 11.7, 95% CI 2.24–63.6). The significance of intact ulnar (ring and small) fingers is further emphasized when comparing the primary outcome measures between patients with amputations of 1–3 radial digits (n = 31) and 4–5 digits (n = 10). The first group of patients scored statistically significantly better in the Sollerman hand function test, modified

### Table 2. Primary and secondary outcomes

<table>
<thead>
<tr>
<th></th>
<th>Second toe transfer (n = 35)</th>
<th>Big toe transfer (n = 5)</th>
<th>Total (n = 41)</th>
<th>Control (n = 38)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Follow-up, months</strong></td>
<td>169 (38–288)</td>
<td>323 (301–358)</td>
<td>187 (38–346)</td>
<td></td>
</tr>
<tr>
<td><strong>Number of rays amputated (mean)</strong></td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td><strong>Dominant hand injury</strong></td>
<td>19</td>
<td>4</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td><strong>ADL (modified Tamai) [0–20]</strong></td>
<td>15.25 (3.75–19.25)</td>
<td>12.5 (7.25–17.75)</td>
<td>14.25 (3.75–19.25)</td>
<td></td>
</tr>
<tr>
<td><strong>ADL (our questionnaire) [12–48]</strong></td>
<td>43 (20–48)</td>
<td>37 (27–46)</td>
<td>42 (20–48)</td>
<td></td>
</tr>
<tr>
<td><strong>Sollerman test [0–80]</strong></td>
<td>78 (46–80)</td>
<td>77 (73–80)</td>
<td>78 (46–80)</td>
<td>80 (68–80)</td>
</tr>
<tr>
<td><strong>Modified Tamai score [–10 to 100]</strong></td>
<td>77 (28–99)</td>
<td>68 (37–86)</td>
<td>72 (28–99)</td>
<td></td>
</tr>
<tr>
<td><strong>IP joint active range of movement (°)</strong></td>
<td>25 (0–70)</td>
<td>45 (20–55)</td>
<td>25 (0–70)</td>
<td>75 (45–115)</td>
</tr>
<tr>
<td><strong>IP joint extension lag (°)</strong></td>
<td>28 (0–120)</td>
<td>5 (0–30)</td>
<td>25 (0–120)</td>
<td>0 (–60–5)</td>
</tr>
<tr>
<td><strong>First web opening (mm) in patients with intact second ray</strong></td>
<td>122 (84–176)</td>
<td>129 (120–140)</td>
<td>122 (84–176)</td>
<td>157 (110–192)</td>
</tr>
<tr>
<td><strong>Cylinder grip width (cm)</strong></td>
<td>10 (6–11)</td>
<td>11 (7–11)</td>
<td>10 (6–11)</td>
<td>11 (9–11)</td>
</tr>
<tr>
<td><strong>s2PD ≤10 mm</strong></td>
<td>13</td>
<td>1</td>
<td>14</td>
<td>38</td>
</tr>
<tr>
<td><strong>m2PD ≤10 mm</strong></td>
<td>17</td>
<td>2</td>
<td>20</td>
<td>38</td>
</tr>
<tr>
<td><strong>Key pinch (kg)</strong></td>
<td>6.5 (0.5–12)</td>
<td>6 (3–10)</td>
<td>6.5 (0.5–12)</td>
<td>10.5 (3.5–15)</td>
</tr>
<tr>
<td><strong>Pulp pinch (kg)</strong></td>
<td>4.5 (1–9.5)</td>
<td>3.5 (1.5–7)</td>
<td>4.5 (1–9.5)</td>
<td>6 (3.5–10.5)</td>
</tr>
<tr>
<td><strong>Grip strength (kg)</strong></td>
<td>32 (0–63)</td>
<td>32 (18–47)</td>
<td>32 (0–70)</td>
<td>48 (15–73)</td>
</tr>
<tr>
<td><strong>Subjective symptoms [0–10]</strong></td>
<td>10 (2.15–10)</td>
<td>10 (6.44–10)</td>
<td>10 (2.15–10)</td>
<td></td>
</tr>
<tr>
<td><strong>Cosmetics [0–10]</strong></td>
<td>7.5 (1.25–10)</td>
<td>5 (2.5–10)</td>
<td>7.5 (1.25–10)</td>
<td></td>
</tr>
<tr>
<td><strong>Satisfaction of operation [0–20]</strong></td>
<td>20 (5–20)</td>
<td>10 (5–20)</td>
<td>20 (5–20)</td>
<td></td>
</tr>
<tr>
<td><strong>Return to pre-amputation work, n (%)</strong></td>
<td>26 (74)</td>
<td>1 (20)</td>
<td>28 (68)</td>
<td></td>
</tr>
<tr>
<td><strong>Pain at rest [1–4]</strong></td>
<td>4 (2–4)</td>
<td>4 (3–4)</td>
<td>4 (2–4)</td>
<td></td>
</tr>
<tr>
<td><strong>Pain at exertion [1–4]</strong></td>
<td>4 (2–4)</td>
<td>3 (2–4)</td>
<td>4 (2–4)</td>
<td></td>
</tr>
<tr>
<td><strong>Social acceptance [1–4]</strong></td>
<td>4 (1–4)</td>
<td>3 (2–4)</td>
<td>4 (1–4)</td>
<td></td>
</tr>
<tr>
<td><strong>Cold intolerance [1–4]</strong></td>
<td>3 (1–4)</td>
<td>3 (2–4)</td>
<td>3 (1–4)</td>
<td></td>
</tr>
<tr>
<td><strong>Appearance on 0–100 VAS scale (%)</strong></td>
<td>85 (10–100)</td>
<td>81 (17–98)</td>
<td>84 (10–100)</td>
<td></td>
</tr>
</tbody>
</table>

Results are given as median [range] unless otherwise indicated.

*One patient had a third-toe transfer, which is why the total number of patients (41) is greater than the combined number of second and great toe transfers.

**Only uninjured hands were included in the control group. Three patients had amputations in the contralateral hand. VAS: visual analogue scale.
Tamai ADL and our ADL (Table 3). The likelihood of returning to the pre-amputation occupation was higher in patients with intact ring and small fingers (odds ratio 4.9, 95% CI 1.08–22.6).

The injured hand dominance did not affect the results according to the modified Tamai ADL \( (P = 0.140) \), our ADL \( (P = 0.934) \), the Sollerman hand function test \( (P = 0.140) \) or the modified Tamai score \( (P = 0.223) \). Neither did gender (M/F 33/8) have any effect on the primary outcome measures.

Secondary outcomes

The results are presented in detail in Table 2. The median active range of motion of the transferred MTP joint (eight patients) was 15\(^\circ\) (range 0–50\(^\circ\)), and extension lag 5\(^\circ\) (range 0–45\(^\circ\)). The motion achieved with the MTP joint transfer and the median total range of active motion (MTP and IP joints together) were respectively 27% and 31% of those in the contralateral thumbs. Sixteen patients could recognize either the 2.83 or 3.61 Semmes–Weinstein filaments. Good results in moving two-point discrimination (m2PD) predicted good results in the modified Tamai ADL questionnaire and Tamai score (Table 4). Likewise, patients who could make a distinction between a sharp and a dull touch had less subjective symptoms (modified Tamai questionnaire, \( P = 0.02 \)) and scored better in our ADL questionnaire \( (P = 0.077) \) and the modified Tamai score \( (P = 0.058) \).

The median key pinch, pulp pinch and grip strengths of the hand with the toe transfer were 62, 75 and 67%, respectively, of those in the contralateral uninjured hand. Good results in the key pinch had a

Figure 3. Examples of tasks included in the Sollerman hand function test. The test evaluates different forms of grip. [A] Precision pinch, [B,C] small object manipulation and [D] and directional grip all require adequate sensation and control of movement. [E] Hexagonal nut grip. [F] Screwdriver grip. This male patient had a frostbite injury at the age of 32 after getting lost on a cross-country skiing trip. Thumb reconstruction just distal to the MCP joint resulted in a good functional outcome with the patient scoring a full 80 points from the tests illustrated.
highly statistically significant positive correlation with primary subjective and objective outcome measures (Table 4). The key pinch was also stronger (median 7.5, interquartile range 5.5–9.5) in those who returned to pre-amputation occupation when compared with the same grip in patients who returned to lighter work or who were unable to work (median 4.75, interquartile range 2.75–6.125 and median 5.5 interquartile range 0.5–9.5 respectively; \( P = 0.014 \)). Likewise, grip strength predicted a good result in our ADL, the Sollerman hand function test and modified Tamai ADL questionnaire (Table 4).

Four patients, in spite of not being satisfied with the result of the operation, would have chosen the toe-transfer operation again. One of these patients specifically mentioned that he would not want to donate the big toe again. These patients scored somewhat poorer on the tests measuring function and cosmetics and only one of them had returned to pre-injury occupation.

In our questionnaire, pain at rest, lack of or poor quality of sensibility, hyperaesthesia, general acceptance and cosmetic outcome all had an average rating of no complaint (\( >3.5 \) points). Cold intolerance was considered most disturbing, with an average of 2.7 points.

**Radiological outcomes**

Osteoarthritis of IP joints in the transferred toes was graded as mild in 12 patients and non-existent in the rest. In addition, three out of eight transferred MTP joints had mild osteoarthritis. Patients with osteoarthritis were slightly older (mean 49 years) than those without (mean 41 years). Furthermore, those with osteoarthritis in the transferred IP joints had a

### Table 3. Associations between lower scores in primary outcome measures and type of transfer, number of nerves reconnected and injury patterns

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Our ADL &lt;30</th>
<th>Modified Tamai ADL &lt;12.5</th>
<th>Sollerman &lt;70</th>
<th>Modified Tamai score &lt;59</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transfer</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Big toe</td>
<td>5</td>
<td>7.11 [0.83–60.7]</td>
<td>1.00 [0.15–6.77]</td>
<td>—</td>
<td>3.87 [0.51–29.3]</td>
</tr>
<tr>
<td>Second toe</td>
<td>35</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Third toe</td>
<td>1</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td><strong>No. of nerves/transfer</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>4.33 [0.30–63.3]</td>
<td>3.80 [0.31–47.2]</td>
<td>27.0 [1.65–442]*</td>
<td>2.30 [0.17–30.6]</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>1.08 [0.10–11.9]</td>
<td>1.52 [0.33–6.96]</td>
<td>3.86 [0.46–32.4]</td>
<td>0.57 [0.06–5.69]</td>
</tr>
<tr>
<td>4</td>
<td>29</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td><strong>No. of rays amputated</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1–3</td>
<td>31</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>4–5</td>
<td>10</td>
<td>6.21 [0.87–44.6]</td>
<td>5.70 [1.20–27.1]*</td>
<td>9.67 [1.43–65.4]*</td>
<td>2.79 [0.50–15.5]</td>
</tr>
<tr>
<td><strong>Method of amputation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avulsion</td>
<td>12</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Crush</td>
<td>15</td>
<td>—</td>
<td>22.00 [2.18–222]*</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Explosion</td>
<td>6</td>
<td>—</td>
<td>22.00 [1.54–314]*</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Other</td>
<td>8</td>
<td>—</td>
<td>1.57 [0.08–29.4]</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Logistic regression models were used with the results expressed as odds ratio [95% CI]. A dash (—) indicates that there were no cases in this category.

*\( P < 0.05 \).

### Table 4. The Spearman correlations \( r \) and their \( P \)-values between physical variables, primary outcome measures and satisfaction according to the modified Tamai score

<table>
<thead>
<tr>
<th></th>
<th>n = 41</th>
<th>Cylinder grip width r (( P ))</th>
<th>Key pinch r (( P ))</th>
<th>Grip strength (Jamar) r (( P ))</th>
<th>m2PD* P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our ADL</td>
<td>0.57 ((&lt;-0.001))</td>
<td>0.72 ((&lt;-0.001))</td>
<td>0.63 ((&lt;-0.001))</td>
<td>0.093</td>
<td></td>
</tr>
<tr>
<td>Modified Tamai ADL</td>
<td>0.57 ((&lt;-0.001))</td>
<td>0.65 ((&lt;-0.001))</td>
<td>0.42 (0.006)</td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>Sollerman hand function test</td>
<td>0.51 (0.001)</td>
<td>0.66 ((&lt;-0.001))</td>
<td>0.52 ((&lt;-0.001))</td>
<td>0.287</td>
<td></td>
</tr>
<tr>
<td>Modified Tamai score</td>
<td>0.44 (0.006)</td>
<td>0.60 ((&lt;-0.001))</td>
<td>0.31 (0.054)</td>
<td>0.027</td>
<td></td>
</tr>
<tr>
<td>Satisfaction (modified Tamai score)</td>
<td>0.17 (0.292)</td>
<td>0.39 (0.011)</td>
<td>0.10 (0.542)</td>
<td>1.000</td>
<td></td>
</tr>
</tbody>
</table>

*Fisher’s exact test was used for m2PD (\( \leq 10 \) mm or \( >10 \) mm). \( P < 0.05 \) was considered significant.
slightly longer follow-up (mean 205 months) than those without (184 months). The presence of radiographic osteoarthritis did not correlate with any of the primary outcomes.

Radiographs were also assessed for the presence of osteopenia. Patients with no signs of osteopenia (n=26) were more likely to score better in our ADL (P=0.027), modified Tamai ADL (P=0.051) and the Sollerman hand function test (P=0.049), than patients with osteopenia (n=15) visible on the radiograph of the reconstructed hand. Key pinch (P=0.004) and grip strength (P=0.001) were also better in patients without osteopenia. Patients with bone quality in the reconstructed hand that was identical to the contralateral hand (n=28) were statistically significantly more likely to score better in all of the primary outcome measures, as well as key pinch and grip strengths, than patients who had poorer bone quality in the reconstructed hand than in the contralateral hand (n=11). There was no connection between the results of sensory measurements and osteopenia so osteopenia is most likely to be not the reason for, but rather a sequel of, diminished use of the reconstructed hand. Pain at rest or during use was not related to radiographic bone quality or arthritis.

Complications

All the transfers survived. Two patients needed an emergency re-operation during the immediate postoperative period. Revision and re-anastomosis was successful in both cases. Another patient had a flexor tendon rupture repaired three times, the first of the repairs being 16 days after the thumb reconstruction.

There were superficial infections in five of the reconstructed hands. Three of them were related to K-wires, which were subsequently removed and antibiotics administered. No cases of osteomyelitis occurred.

Wound healing in the foot was compromised in six patients. The resulting infections were treated with wound irrigation and antibiotics and no secondary operations were needed. One patient developed a transient peroneal palsy of the donor foot from the tourniquet, which was inflated for a total of 4 hours, with an interval in between. Fortunately, the function of the lower extremity recovered completely in 2 weeks.

Secondary operations

In total, 16 late corrective re-operations were done in eight patients. Fifteen of them were done in seven patients to improve the function or appearance at the recipient site. The secondary operations included opponensplasty, rotational osteotomy, metatarsal epiphysiodesis (and later an MTP joint arthrodesis in the same patient), and skin procedures (rotational flaps, Z- or V to Y-plasties). Scar problem was the indication for the re-operation in one foot.

Discussion

Even though there are numerous articles about patients with toe-to-thumb transfers, few report assessment of function by tests or questionnaires. No single test has emerged as generally accepted and in fact only Chung and Wei (2000) and Fan et al. (2006) have used the same test (the Michigan Hand Outcome Questionnaire [MHQ]). Physical parameters such as motion, strength or sensation contribute to function but do not equate with it. In this study, we have tried to define and present a unified patient group. All the patients had a single toe transferred and most of the patients had a similar reconstructive surgical procedure (second toe transfer).

This study was retrospective in nature and therefore information about the accident resulting in the amputation, the reconstructive operation and postoperative care are subject to flaws. Furthermore, since no evaluation of function was made before the reconstructive operation, it is an assumption that an increase in function was achieved. The patient group and the design of the study exclude a comparison of the results between the big and the second toe transfer patients because of possible selection bias and the small number of patients in each subgroup.

Evaluation of function as a subjective outcome

Fan et al. (2006) reported that the ADL sections of the MHQ significantly improved with second toe or wrap-around thumb reconstruction when pre- and postoperative values were compared. The preoperative value was based on patients’ recollections of the function before the reconstructive operation. There was a statistically significant overall improvement in all domains, apart from the pain level, of the MHQ in their report. Similarly, Chung and Wei (2000), using the same questionnaire, reported better results in all domains, except pain level, in 16 patients with thumb reconstruction at the metacarpophalangeal (MCP) level (by second or big toe transfer) compared with five patients with injury at the same level who had refused toe-to-thumb transfer.
transfer. Additionally, the reconstructed hand scored significantly worse in the domains of ADL, Aesthetics and Satisfaction but not in Function when compared with the normal contralateral hand. In our study, no comparison was made between the obtained results and patients’ recollections of function before reconstructive operation, since the long time that had elapsed might have distorted this comparison. Nonetheless, our patients scored markedly well in both the ADL questionnaires. Most activities [11/20] were considered easy or quite easy (modified Tamai ADL) and most patients [36/41] managed with no or minor complaints (our ADL).

**Evaluation of function as an objective outcome**

Michon et al. [1984] reported good or excellent functional results in three out of seven patients with thumb amputations treated by big or a second toe transfers. Chung and Wei [2000] did not find significant differences in the Jebsen–Taylor test when comparing the reconstructed and the uninjured contralateral hand. Patients who had refused thumb reconstruction scored worse when the injured hand was compared with the uninjured contralateral hand. In our patients, the Sollerman hand function test and the modified Tamai score demonstrated good results in the reconstructed hands. Eighty-eight per cent of the patients completed the Sollerman hand function test without difficulties and 83% had good or excellent results in the modified Tamai score. The uninjured control hand scored somewhat better in the Sollerman hand test when compared to the hand with the toe transfer (median 80 and 78, respectively). As in the study of Chung and Wei [2000], this did not reach statistical relevance ($r=0.21$, $P=0.195$).

However, in the control group, only one hand scored $<70$ points, whereas six hands with toe transfer scored $<70$ points.

When looking at activities that required precision in hands with microvascular thumb reconstructions, Frykman et al. [1986] reported that tasks like buttoning-up, winding a watch or picking up a pin or a match were impossible after thumb reconstruction with a second or big toe transfer. Poppen et al. [1983] reported that out of ten patients, four could not make a precision sensory grip and three could not grasp small objects. In contrast, Doi et al. [1985] stated that pick-up testing was satisfactory. In our patients activities that required fine manipulation, such as using a screwdriver, turning hexagonal nuts (Figure 3E,F) or buttoning-up, were difficult, but not impossible. The mean scores indicated slight difficulties, the Sollerman hand function test results being 3.0, 3.2 and 3.2 respectively for these activities. This was similar to the findings of Frykman et al. [1986] and Poppen et al. [1983].

**The influence of the extent and type of injury on function**

Leung [1983] reported good or excellent functional results for patients with MCP or metacarpal level thumb amputations reconstructed by a second toe transfer. Patients with injuries at the carpometacarpal level or to the radial hemi-hand that were reconstructed the same way scored worse. The extent of the injury both proximally in the thumb and ulnarswards to involve other fingers also affected the functional results in our patients. Patients with preservation of the MCP joint or thenar muscle function scored better than more proximally amputated patients in the Sollerman hand function and the modified Tamai tests (Sollerman 76 and 68, respectively; modified Tamai 74 and 63). However, this did not reach statistical significance (Table 3).

Poppen et al. [1983] reported that the patient’s conception of the ability to use the reconstructed hand in handling small objects was restored to 80% of normal. They found that patients with multiple digital loss scored markedly worse (22%) than single thumb ray amputees (80%). Our patients with only thumb amputations managed better in the modified Tamai ADL questionnaire when compared with multiple finger amputees. An intact ulnar part of the hand seems important in achieving good result with microvascular thumb reconstruction. In our patients those with uninjured ring and small fingers recovered better function than patients with four or five fingers amputated.

Our results indicate that patients with crush or explosion injuries were more likely to score worse in the modified Tamai ADL questionnaire when compared with those with avulsion or other types of injuries. Patients with avulsion type injuries were most likely to return to their pre-amputation occupations. This is likely to be due to the fact that avulsion injuries involved only the thumb [except in two patients] and the thenar muscles were always left intact.

Three patients had a surgical amputation of the thumb to treat a medical condition. They scored to some extent better in primary outcomes when compared to the whole patient material. Additionally, they had less subjective symptoms related to the transplant and were more pleased with the cosmetic appearance of the transplant according to the modified Tamai questionnaire. Nevertheless, one of the patients was not satisfied with the result of the operation.
The physical variables and their effect on function

The active IP joint movement in the reconstructed thumb after second or big toe transfers varies from 90° (Leung, 1983) to 20° (Wilson et al., 1984). Wei et al. (1994) reported a mean active flexion of the IP joint of 25° (range 0–40°) with second toe transfers \((n=10)\) and 20° (0–40°) with trimmed toe transfers \((n=20)\). In our patients, the median active movement of the IP joint was 25° with an extension lag of 25°. Patients with the big toe transferred had an average 10° more active movement and 21° less extension lag when compared with patients with a second toe transfer. The problem of extension lag in second toe transfer was addressed both at the operation (Figure 2) and in the rehabilitation (by using a dynamic splint). None of the technical features used in the operation had a statistically significant influence on the extension lag. This is probably due to the normal posture of the toe in the foot. The clawing of the second toe transfer reflects the balance of the tendons and probably cannot be overcome by reconstruction. As a measure of the ability to open the web between the thumb and the opposing finger, the width of cylinder grip had a clear positive and significant correlation with all the primary subjective and objective outcome measures (Table 4). This may reflect the importance of postoperative rehabilitation and extension splinting.

The reported sensation varies from static two-point discrimination (s2PD) of 2–6 mm in 6/28 patients reported by Leung (1983), to just protective sensation. In the largest reported group of 240 patients with a 5-year follow-up the s2PD was <10 mm in 90% (Gu et al., 1997). Only 14 of our 41 patients had s2PD <10 mm. Nevertheless, only three patients reported the lack or poor quality of sensation to be a moderate complaint. Moving two-point discrimination (m2PD) and distinction between a sharp and dull touch both had positive and significant correlations with the modified Tamai ADL questionnaire and the Tamai score as well as subjective symptoms. Lee et al. (1995) noted that patients \((n=9)\) with three nerves reconstructed had better sensation than a patient with only one nerve reconstructed (s2PD 8.2 and 15 mm, respectively). According to our results, the number of nerve reconnections did not have a statistically significant influence on the achieved sensation for each transfer, measured with Semmes–Weinstein filaments, s2PD or m2PD. However, patients who had only two nerves connected scored worse in the Sollerman hand function test than patients with three or four connected (Table 3). Reconstruction of the dorsal nerves may increase sensory feedback about posture and movement and so improve the use of the transferred toe.

When hands that had been reconstructed with the second toe, wrap-around and trimmed toe methods were compared with the other hand, Wei et al. (1994) reported restorations of 40, 80 and 75% of key pinch and 60, 75 and 66% of the grip strengths for the respective reconstructions. Frykman et al. (1986) noted that the condition of the thenar muscles influenced the key pinch and grip strengths that could be achieved in patients with a thumb reconstruction using either big or second toe transfers. In patients with intact thenar muscles the key pinch and grip strengths were restored to 63 and 75% respectively of the control hands in patients with intact thenar muscles and to 6 and 9% in those in whom the muscles were not intact. Similarly, our patients with intact thenar muscles (amputation level 1–2) had better restoration of key pinch and grip strength (74 and 78% of the strengths in the control hands, respectively) than those with more proximal injuries (amputation level 3–4) (26 and 52%, respectively). The dominance of the injured hand did not affect the key pinch or grip strengths that were achieved. In dominant hand injuries the key pinch and grip strengths were 65 and 74%, respectively, and 66 and 76% in the non-dominant hands.

The advocates of big toe transfer state that, “great toes make great thumbs” (Valauri and Buncke, 1989) and that the stability and appearance are better than with a second toe transfer (Wei et al., 1994). Our results do not allow us to refute or support these claims. More information is needed to be able to compare different reconstruction methods in similar patient groups using comparable tests that measure function both subjectively and objectively. Based on our encouraging results for the function and satisfaction that can be achieved by a second toe transfer, minimizing donor site problems may be decisive in the end.

Our results indicate that restoring strong key pinch and grip strength together with good opening ability in the reconstructed web are important in achieving satisfactory subjective and objective functional outcomes. Moreover, good recovery of sensation, especially m2PD, predicts better outcome. We conclude that microvascular toe transfer is a good option for rehabilitating patients with thumb amputations when it comes to restoring function, with high patient satisfaction. The extent of the injury, both to the thumb ray and to other fingers, influences the function that can be achieved. However, even a single toe transfer can re-establish sufficient pinching and gripping ability, provided that there is a good enough opposition post. The second toe transfer is as
good as the big toe in restoring adequate thumb function. In addition, the second toe with three joints allows reconstruction of thumb amputations at the proximal metacarpal and carpometacarpal joint levels with the least donor site problems.

Conflict of interests
None declared.

References


Long-term results of finger reconstruction with microvascular toe transfers after trauma**

Tero Kotkansalo a,*, Simo Vilkki b, Petra Elo c

aDepartment of Orthopaedic and Traumatologic Surgery, Turku University Hospital, Turku, Finland
bDepartment of Hand and Microsurgery, Tampere University Hospital, PL 2000, FIN-33521 Tampere, Finland
cPirkanmaa Hospital District, Medical Imaging Centre, Tampere, Finland

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KEYWORDS
Grip reconstruction;
Functional outcome;
Toe-to-finger;
Reconstructive microsurgery

Summary Amputation of all or most of the fingers severely disturbs the gripping function of the hand. The purpose of this study was to evaluate the long-term functional results of finger-amputation patients rehabilitated with microvascular toe transfers.

Fifteen such patients (10 males, median age at injury 26 years (range 5–49 years)) were examined after a median follow-up of 18 years. Eight patients had no fingers spared by the initial trauma and the rest had at least two fingers amputated. The function of the hand was accessed subjectively (questionnaires) and objectively (tests). Further, physical parameters were measured and compared to the other healthy hand.

Patients scored consistently well in the test measuring function (the Sollerman hand function test and the modified Tamai score). Activities of daily living presented on average minor difficulties. Patients regained on average 42% of grip and 84% of key pinch strength compared to the other hand. The average movement of the transfer was 28°. One transfer was lost due to inability to restore permanent circulation. In addition, there were one donor and one recipient site superficial infections.

We conclude that microvascular toe transfer is a reliable way to improve gripping function after amputation of fingers. Patient approval is generally good and the achieved function satisfactory. Two toe transfers should be considered for patients with no fingers left. Work-related injury may be related to decreased occupational capability.

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** This study was carried out at the Department of Hand and Microsurgery, Tampere University Hospital, PL 2000, FIN-33521 Tampere, Finland.
* Corresponding author. Tel.: +358 2 3130638; fax: +358 2 3131276.
E-mail address: tero.kotkansalo@tyks.fi (T. Kotkansalo).

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Complete amputation of several or all of the fingers renders the hand with poor function. If replantation is not possible or successful, microvascular transplantation of toes should be considered to restore dexterity.

Current literature on microvascular finger reconstruction presents studies varying from fingertip reconstruction to multiple toe transfers for all four finger-amputations. Typically, the second or the third toe, independently or as a double toe transfer, has been used. While survival, physiological parameters and complications are often reported, a systematic evaluation of function is limited and easily distorted by inclusion of multiple patient groups.

The purpose of this study was to examine the long-term functional results of microvascular single or double toe-to-finger grip reconstruction after traumatic amputation of fingers.

**Patients and methods**

A total of 22 patients were identified to fulfil the inclusion criteria. Fifteen patients (21 transfers) were able to attend the clinical follow-up where they were examined according to the study protocol by an observer who had not participated in the care of the patients. Patient characteristics are presented in Table 1.

**Injuries**

All the patients had a traumatic amputation of at least two fingers. The extent of the injury and the reconstruction used are illustrated in Figure 1. Patient 4 had a complete degloving injury of the thumb as well. His contracted thumb was covered on the palmar side with a hemipulp flap from the great toe. The amputation was unilateral in all patients. The patient material can be further divided into those who had no functional fingers left (patients 2, 4, 7, 9, 10, 12, 13 and 15) and those who had at least some useful fingers left (patients 1, 3, 5, 6, 8, 11 and 14). Ten of the patients had a workman’s compensation.

**Reconstructive operations and post-operative practice**

Finger reconstruction was done with a single second toe in nine patients. A double second—third en bloc toe transfer was used in patients 5, 8, 9 and 10. Two second toes were used in a single operation in patient 15 and in two separate operations in patient 12. The metatarso-phalangeal (MTP) joint was used in the reconstruction in patient 8 (Figure 2). Direct wound closure was possible in only two patients. For the rest, a split-thickness skin graft or a hemipulp flap from the great toe (patient 4) was used.

The method of harvesting of the toe transfer has been presented by the same authors in 2007.11 The double second—third en bloc transfer was first left in syndactyly for 1 month in order to save the normal finger web at the hand (Figure 3). In a second operation, the syndactyly was released in order to allow better independent motion and more normal abduction.

A dynamic splint was fabricated to each patient 1 week postoperatively. During the first 1–2 months, special attention was given to achieve good extension of the newly reconstructed finger.

**Study protocol**

Similar study protocol has been used in the previous studies by the same authors.11–13 The outcomes of the study were divided into primary (function) and secondary (physiological parameters, satisfaction, etc.). Further, the method of reaching these outcomes was divided into subjective (questionnaires) and objective (tests).

All the patients were sent a questionnaire. This was modified from the one proposed by the International Federation of Societies for Surgery of the Hand (IFSSH) subcommittee on replantation (the Tamai questionnaire).14 A second questionnaire, designed by the authors for the toe transplant patients, was filled out during the clinical follow-up visit.12

The Sollerman hand function test was used as an objective measurement of primary outcome.15 In addition, a score proposed by the IFSSH subcommittee on replantation (the Tamai score) for finger replantation patients was used as well.14

We combined the three individual scores (our Activities of Daily Living (ADL), the Sollerman hand function test and the modified Tamai score) by adding up the results. This provides a wider perspective to evaluating function. A good result (≥172 points) was reached by scoring no complaint (≥42) in our ADL, excellent result (≥80) in the modified Tamai score and no more than slight difficulties (≥50) in the Sollerman hand function test.

Secondary subjective outcomes, such as pain or satisfaction, were received from both questionnaires. Further, sensibility, strength and range of movement were assessed as secondary objective outcomes. For the purpose of this study, the distal inter-phalangeal (DIP) — and the proximal

| **Table 1** Patient and injury characteristics. |
|-----------------|-----------------|
| **Number of patients** | 15 |
| **Male/female** | 10/5 |
| **Age at injury (y)\(^a\)** | 26 (5–49) |
| **Dominant hand injury** | 11 |
| **Interval to reconstruction (mo)\(^a\)** | 6 (1–170) |
| **Type of injury** | **Crush** 10  |
| **Saw** | 3 |
| **Avulsion** | 2 |

\(^a\) Median and (range) reported.
Figure 1  A schematic presentation of the extent of the injury and the reconstruction used for each of the patients. Additionally, gender, age at injury, interval between the injury and the reconstruction (months) as well as injured hand dominance presented. Transferred toes coloured in dark grey and the one failure in patient 9 in light grey. Patient 4 had a deglowing of the thumb. The soft tissue defect was reconstructed with a hemipulp flap from the great toe (light red/yellow).
inter-phalangeal (PIP) — joints were considered as one inter-phalangeal (IP) joint. All the measurements of secondary objective outcomes were done to the contra-lateral uninjured hand as well.

During the clinical follow-up, radiographs were taken from both hands and reconstructed fingers and their counterparts in the uninjured hand. The radiographs were examined for any signs of arthritis and the quality of bone, in terms of osteopaenia, was assessed.

Information about complications and secondary operations was gathered from patient charts and during clinical follow-up. Due to the skewed distributions, continuous

Figure 2  A case of double toe transfer with one MTP joint included in the flap presented here. Patient 8 caught her right dominant hand in a meat grinder at the age of 21. Pre- (A) and post-operative (B) photographs. Radiographs (C and D) illustrating different levels of reconstruction. A second toe with three joints was used to reconstruct the middle finger. Transferred toes acting in opposition with the thumb in grasp (E) and pinch (F).
variables were expressed by medians and ranges; otherwise, average was presented.

Results

We present a median follow-up of 216 months (18 years), range 90–349 months, of 15 patients (median 207 months for 20 transplanted toes) with a microvascular toe-to-finger reconstruction.

Primary outcomes

The results of primary outcomes are presented in Table 2. According to the modified Tamai questionnaire, nine of the patients reported managing the ADL on average easy or quite easy. Moreover, nine of the 20 questions were rated on average easy or quite easy. For instance, showing ‘scissors’, ‘paper’ and ‘stone’ and picking up needle were regarded as difficult, averaging 0.25 and 0.36, respectively. Conversely, tasks such as pushing, tapping, hanging or drawing and grasping a soft material were considered easier, averaging 0.81–0.86.

Twelve of 15 patients scored over 30 in our questionnaire, which means that they could cope with ADL with no or minor complaint. Further, all of the questions rated on average as minor or no complaint. The most difficult tasks were handling small objects, strong grip, handle grip and fumbling in pocket, averaging between 2.6 and 2.8.

The patients scored consistently well in the Sollerman hand function test. Only patients 4, 7 and 13 completed the test with slight difficulties (54–69 points), the rest (12 patients) had on average no difficulties (70–80 points). Of the individual tasks tested those requiring small-object manipulation, such as using a screwdriver or buttoning up, were completed with slight difficulties (3–3.4 points). The rest of the tasks were completed on average without difficulties (3.5–4 points).

The modified Tamai score showed a greater difference of results than the Sollerman hand function score. Yet, 12 patients received good or excellent result (60–100 points) in the test.

According to the combined score, patients with no fingers spared by the initial trauma scored worse than those with some finger function left (average 159 vs. 198). Further, among patients with no fingers left, those who were reconstructed with a single toe transfer scored <172 points and those reconstructed with two toe transfers all scored >172 points.

Secondary outcomes

The median for the subjective symptoms related to the transplant was 8.57 (6.42–10) and for the cosmetics it was 5 (0–10), referring to mild symptoms and moderate appearance, respectively. Additionally, satisfaction towards the operation was good in 14 patients. There was, however, one patient (number 13) who, in retrospect, would not have wanted to go through the reconstructive operation.

Cold intolerance was rated a moderate complaint (median 2.2 (1–4)), whereas general approval, social acceptance and allodynia were considered less of a problem (median 3.6–3.7 (1–4)). The median for the visual analogue scale (VAS) of the cosmetic appearance was 81 (10–100).

The results of secondary objective outcomes and their proportion of the control finger’s measurements are presented in Table 3. Since only one transfer including the MTP joint participated in the study, most (median 78% (56–100)) of the total range of active motion is attributed to the intact MCP joint. The transferred MTP joint in patient 8 had 20° of hyperextension and active flexion of 50°. There was...
Table 2  Primary outcomes.

<table>
<thead>
<tr>
<th>Patient number</th>
<th>Follow-up of transferred toes (mo)</th>
<th>Injury to transfer interval (mo)</th>
<th>Modified Tamai ADL (0–20)</th>
<th>Our ADL (12–48)</th>
<th>Sollerman (0–80)</th>
<th>Modified Tamai score (–10–100)</th>
<th>Combined scorea</th>
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</table>

a Combined score is the sum of results of Our ADL, the Sollerman hand function test and the modified Tamai score.

Table 3  Secondary objective outcomes.

<table>
<thead>
<tr>
<th>Sensibility</th>
<th>Strength (kg)</th>
<th>Movement (°)</th>
<th>Median % of control</th>
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<td>Static 2PD</td>
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<tr>
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</tr>
<tr>
<td>Median</td>
<td>j4.31</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Movement and static 2 PD: 1 = > 10 mm, 2 = ≤10 mm.

(1) % value of control finger/hand values presented in brackets.

a Measured between the thumb and the radial most transfer in cases where two toes were transferred.

b Not measured.

c Extension lag of the control finger is 0°.
Long-term results of finger reconstruction with microvascular toe transfers after trauma

no obvious instability, bearing in mind that the joint was surrounded by intact MCP joints.

All the patients returned to either previous (n = 9) or lighter (n = 6) work. Those returning to previous work scored better in the primary and secondary subjective outcome measures when compared to those who returned to lighter work. Interestingly, all of those returning to lighter work had a work-related injury, while only 4/9 returning to previous work were injured at work. Further, work-related injury seemed to be related to poorer subjective and objective outcomes when compared to other injury settings.

Radiological results

There were five transfers (patients 2, 7, 10, 13 and 15) with moderate arthritis of the IP joints of the transferred toes. The rest of the transfers, including the one transferred MTP joint, had either no or mild arthritis. Patients with moderate arthritis scored worse in the modified Tamai score (median 64 vs. 72) and ADL (8 vs. 15) when compared to patients with mild or no arthritis. Similarly, patients with mild or noticeable osteopaenia of the transferred toes (patients 2, 4, 9, 11 and 13) scored worse than those without (n = 10) in the modified Tamai score (median 58 vs. 74) and ADL (6 vs. 15). However, it is likely that osteopaenia is not the reason for poorer function but rather a consequence of initial trauma.

Complications

One transplant was lost due to the inability to re-establish permanent circulation. Patient number 9 had three re-operations, including arterial and venous anastomoses revisions, with loss of the other of the double toe transfers. Despite the loss of the other transfer, he completed the Sollerman hand function test without difficulties. The rest of the 20 transfers survived without necrosis. The wound healing was uncompromised in 14 of the 20 operations. There was, however, one donor (patient 2) and one recipient (patient 13) site infection. Both the infections were superficial and healed with per oral antibiotics.

Secondary operations

There were three secondary operations done to two patients. Patient 3 had a pseudo-arthritis resection and re-osteosynthesis. Further, patient 5 had first flexor tendon release and later the tendon was reconstructed with a graft. Secondary foot operations were performed on three patients (numbers 2, 10 and 14). These included two minor operations: one scar revision and a resection of a painful neuroma. Further, patient 10 had a first metatarsal osteotomy with abductor tendon tightening.

Discussion

Previously, only two studies have used a questionnaire, and we were not able to find a single study to use an objective test to evaluate the function of patients with microvascular toe-to-finger reconstruction. In our study, we have tried to assess these patients both subjectively and objectively to find out what level of function can be obtained with microvascular toe-to-finger reconstruction.

This study is retrospective in nature. Therefore, the data concerning the injury and the reconstruction as well as the complications and secondary operations are subject to flaws. Moreover, the small number of patients fulfilling the inclusion criteria and attending the clinical follow-up restricts the conclusions drawn from the results.

Evaluation of function as a subjective outcome

Frykman et al. reports that all of their 12 patients found their reconstructed hand more useful after the operation. Further, Gordon et al. noted that six out of 16 patients had minor difficulties in handling small objects. We did not measure improvement since it involves evaluation of function prior to the reconstruction. Yet, only two tasks, namely picking up a needle and showing 'scissors', 'paper' and 'stone', were reported as difficult. Conversely, there were difficulties in ADL in six (modified Tamai questionnaire) and complaints in three (our questionnaire) patients. Still, the function might have been improved in these three patients due to the operation but was still considered inadequate. Additionally, small-object handling resulted in moderate to major complaints in seven patients (our ADL questionnaire).

Evaluation of function as an objective outcome

Leung reports that all the 12 patients who had had a microvascular second toe transfer to reconstruct either the thumb or the finger function could pinch a paper or a pin equally well with the reconstructed hand and the control hand, whereas gripping of a 5-cm-diameter wooden cylinder was always weaker with the reconstructed hand. Similarly, pinching was part of several tasks included in the Sollerman hand function test performed by our patients. All of these tasks were completed on average without difficulties, with the exception of picking up coins from a flat surface and placing them in a wallet, which caused on average slight difficulties. Likewise, gripping objects of various sizes as part of the tasks of the Sollerman hand function test were completed on average without difficulties. Even so, the diameter of the object (a cartoon or a wooden cube) proved to be too great for some of the patients to be able get a good grip.

Interestingly, the most difficult tasks of the Sollerman hand function test were the ones requiring fast grasping and releasing. Using a screwdriver and turning hexagonal nuts necessitate synchronised controlled movements in opposite directions. Also noticed, although not measured, was that the reconstructed hand was easily neglected as an assisting hand in bimanual assignments. This may be due to the relative long time elapse when the injured hand was not functioning properly (from injury to reasonable recovery after the reconstruction). Besides, the achieved sensation may still be inadequate for the reconstructed hand to naturally assume an assistant role.
Secondary outcomes and their effect on function

We had 14 patients satisfied with the result of the reconstruction. Still, there was one patient who, in retrospect, would have refused to go through the reconstruction (according to modified Tamai questionnaire). This patient (number 13) had a crush injury of all the finger rays of her dominant right hand with only the fifth finger reconstructed with a toe transfer. She scored the worst results in all the subjective and objective tests and questionnaires used in this study. In addition, she reported pain during use, had problems with the social acceptance and was not pleased with the appearance of the reconstructed hand.

The reported active movement of the transferred toe’s IP joints varies from 51° by Wei et al. to 39° by Cosunfirat et al. and finally 33° by Foucher and Moss. Compared to their results, our patients achieved less movement (median 28°). The IP joint movement was only 16% of that of the contralateral fingers. Additionally, the median for the extension lag in our patients was 58°, when Foucher and Moss report an average of 35°. The poorer results of movement and extension lag may be due to different reconstruction tactics or post-operative schemes. The median for the total active range of movement was 115°, much of which (78%) was attributed to the intact MCP joint. The amount of total active range of movement did not relate to primary or secondary outcome measures.

In the largest material so far, Gu et al. achieved s2pd < 10 mm in 216 of 400 patients. Yoshimura tested 33 toe transfers (17 in finger position) with m2pd and reports a median of 8 mm (4–20). Further, Kato et al. using a second toe transfer restored a median of 4.08 (3.84–4.17) sensation measured with Semmes–Weinstein (S–W) filaments. Our results of sensation measured with S–W filaments or m- or s2pd are comparable with the studies mentioned. Patients with better sensation scored somewhat better in the primary outcomes but due to small groups this may be a coincidence.

Our previous report with microvascular toe-to-thumb patients showed that good key pinch and grip strength correlated with good function. The same tendency was apparent in this patient material. However, no statistical analysis was made due to the small number of patients.

Moderate radiological arthritis in the IP joints of the transferred toes seemed to predict poorer function when compared to no or mild arthritis. However, moderate radiological arthritis did not associate with pain, joint deformity or stiffness. Our data do not reveal the reason for the development of arthritis. Patients with moderate arthritis were somewhat older at the time of injury (average 31 vs. 23 years) and at follow-up visit (average 49 vs. 45 years) when compared to those with no or mild arthritis. Still, the difference is relatively small to explain this finding. Other reasons to cause arthritis of the transferred toes IP joints are relative instability or lack of normal protective sensory function during a long period after the operation.

Figure 4  Our present recommendation to reconstruct a hand with no fingers when there are at least two functioning MCP-joints. Patient 15 caught her right dominant hand in a grain mill at the age of 47. Her hand was reconstructed with second toe transfers from both feet at the same operation. Preoperatively (A) she had short finger stumps. Intact MCP-joints enable good abduction/extension (B) and flexion (C) of the transferred toes. She scored well in primary outcome measures and had an adequate width of a grasp (D).
The effect of injury and reconstruction on achieved function

We tried to evaluate function by combining the three individual outcome measures (our ADL, modified Tamai score and the Sollerman hand function score) (Table 2) and set the limit for good result at ≥172 points. Patients with no functional fingers left were reconstructed with either one or two toe transfers. None of these patients reconstructed with a single toe transfer, including patient 9 who lost one of the transfers, reached good results, while all the patients with two toes transferred scored >172. Consequently, our results suggest that two toes are needed in these patients to reach satisfactory function. Further, all of the patients with at least some fingers spared by the initial accident scored over 172 points. Moreover, despite better results achieved with two toes transferred in a no-finger situation, patients with at least some of their own finger function left scored better than those with finger function reconstructed with two toe transfers (average 198 vs. 191, respectively). Therefore, transferred toes are still inferior to fingers.

Four of the patients with all fingers amputated were reconstructed with a single toe transfer (patients 2, 4, 7 and 13). In all but one (patient 13), the transfer was placed in the index position. These patients achieved satisfactory function (combined score between 140 and 170), whereas patient 13 had poor function. This was, most likely, not related solely to the positioning of the transfer but other complicating factors. Otherwise, the interval between the injury and the reconstruction did not seem to influence the outcome (Table 2).

We conclude that microvascular toe-to-finger reconstruction is a reliable (only one partial failure) method to improve hand function after traumatic amputation of fingers. Patient satisfaction is consistent and achievable function adequate. Restoring good sensation and strength of fingers. Patient satisfaction is consistent and achievable improvement hand function after traumatic amputation of fingers.

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Conflict of interest statement

None.

References

Long-term effects of toe transfers on the donor feet

T. Kotkansalo¹, P. Elo², T. Luukkaala³ and S. K. Vilkki⁴

Abstract
The purpose of this study was to assess the long-term consequences to the donor site of microvascular transfer of one or two toes. This was achieved retrospectively by patient-reported, clinician-based and functional testing. Weight-bearing radiographs were taken of both feet. Seventy-four patients (80 feet, 84 transferred toes) participated in this study. After a median of 16 years follow-up, most patients reported no or only minor complaints concerning the donor site. Cold intolerance and pain during exertion were the most commonly reported complaints. According to the two functional scores used, 92% of patients reported no or minor complaint and 83% of patients received a good result at the donor feet. Maintaining first ray alignment and avoiding early postoperative complications predicted a better outcome. Even though donor site ramifications should be expected after microvascular transfer of toes, patient satisfaction remains high.

Keywords
Donor site, toe transfer, AOFAS scale, double-toe, second toe, great toe

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Introduction
When hand function is impaired following a traumatic amputation or congenital absence of fingers or the thumb, a microvascular toe-to-hand transfer can be considered to restore dexterity. A toe transfer brings new elements to the deficient hand but, at the same time, it can cause problems at the donor site.

There are many publications describing the different techniques of toe transfers (Cobbett, 1969; Doi, 1982; Dongyue and Yudong, 1979; Morrison et al., 1980; Tsai and Falconer, 1986; Wei et al., 1988) as well as the outcomes of the transfers. In contrast, reports concerning the possible adverse effects of the donor site are less frequent (Barca et al., 1995; Beyaert et al., 2003; Chung and Wei, 2000; Gu et al., 1997; Lipton et al., 1987; Poppen et al., 1983; Tiamfook et al., 1994; Yang and Gu, 2000). Great toe transfer increases the weight bearing of the second and third metatarsal heads and of the fibular side of the foot (Poppen et al., 1983), but has little effect on velocity, cadence, step width or single and double limb stance time of each foot (Lipton et al., 1987). Likewise, the second toe transfer alters the weight bearing of the foot (Barca et al., 1995). It is, however, considered to cause less problems to the donor site than the great toe transfer (Barca et al., 1995).

The objective of this study was to evaluate the long-term donor site consequences following the transfer of one or two toes. Patient-reported and clinician-based assessment of the feet were performed, as well as radiographic assessment.

Patients and methods
We identified 97 patients (101 feet) who had had a microvascular transfer of one to three toes used for grip reconstruction after traumatic amputation of the thumb, fingers or hand. Additionally, one patient had had a single toe transferred from both feet to

¹Division of Diseases of the Musculoskeletal System, University of Turku, Turku, Finland
²Regional Imaging Centre, University of Tampere, Tampere, Finland
³Pirkanmaa Hospital District and School of Health Sciences, University of Tampere, Tampere, Finland
⁴Department of Hand and Microsurgery, University of Tampere, Tampere, Finland

Corresponding author:
T. Kotkansalo, Division of Diseases of the Musculoskeletal System, Division of Hand Surgery, University of Turku, PL 52, 20521 Turku, Finland.
Email: tero.kotkansalo@tyks.fi
reconstruct a bilateral congenital absence of the hand (acheiria). All the patients were sent a letter containing an informed consent form. A total of 74 patients (80 feet, 85 transferred toes) returned the consent letter and were able to attend the clinical follow-up, where they were examined by an observer who had not taken part in the care of the patients. The results of the recipient site have been reported earlier by the same authors (Kotkansalo et al., 2009, 2011a, 2011b; Vilkki and Kotkansalo, 2007). Six patients (7 feet, 7 transfers) failed to participate in the radiological evaluation of the donor site. Patient demographics are presented in Table 1.

None of the donor feet had prior injuries, and all were asymptomatic at the time of the operation. One patient had a below-knee prosthesis and one had distal digital amputations of all the five toes of the other foot. Further, the patient with bilateral acheiria had a non-vascularized phalangeal transfer from both feet prior to the microvascular toe transfer operations.

### Harvest of the transfers and postoperative practice

There were three different methods of toe harvest.

1. Most of the great toe transfers were done during the early years of microvascular grip reconstruction (1978–1980). The first dorsal metatarsal artery [short pedicle, three patients] or the dorsalis pedis artery [long pedicle, two patients] was harvested with the transfer. The level of bony resection was at the metatarso-phalangeal (MTP) joint [two patients, Figure 1], the proximal phalanx [two patients] or the metatarsal bone [one patient].

<table>
<thead>
<tr>
<th>Table 1: Patient demographics.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patients (n)</td>
</tr>
<tr>
<td>Feet (n)</td>
</tr>
<tr>
<td>Male/female (n)</td>
</tr>
<tr>
<td>Age at injury (y)</td>
</tr>
<tr>
<td>Age at reconstruction (y)</td>
</tr>
<tr>
<td>Delay (injury – reconstruction, months)</td>
</tr>
<tr>
<td>Patients with different reconstructions (n)</td>
</tr>
<tr>
<td>Great</td>
</tr>
<tr>
<td>Single II</td>
</tr>
<tr>
<td>Single III</td>
</tr>
<tr>
<td>Single II + single IV</td>
</tr>
<tr>
<td>Double II</td>
</tr>
<tr>
<td>En-block II–III</td>
</tr>
<tr>
<td>En-block II–III + single II</td>
</tr>
</tbody>
</table>

   aAverage and [range].
   bMedian and [range].

   The donor wound closure was always achieved with the help of a split-thickness skin graft.

2. The method of harvesting the single second-toe transfer used for these patients has been described by the same authors in 2007 (Vilkki and Kotkansalo, 2007). The short arterial pedicle with first dorsal metatarsal artery or second plantar metatarsal artery, either alone or in combination, was used in most cases. A similar technique was used for patients with either a single third- or fourth-toe transfer. In this series of patients with a second-toe transfer, the MTP joint was included in the transfer in 25 patients [27 feet, Figure 2(a)]. As a consequence, these patients had a shortened or absent second metatarsus left in the foot. No attempt was made to reconstruct the deep
Further, 38 patients (40 feet) had a second-toe transfer with the metatarsus left untouched (Figure 2(b)). Of the 75 single toes transferred, 64 included one or two dorsal nerves as well as the plantar nerves.

3. There were five patients with double en-block transfers of the second and third toes (Figure 3). For the arterial reconstruction in these patients, the first, second or even third metatarsal arterial system was used. In all patients, more than one artery was reconstructed. Seven out of ten transfers were dis-articulated at the MTP-joint level. The wound was closed with direct suturing and no skin grafts were needed. All of the double en-block transfers were harvested with plantar and one to three dorsal nerves.

The donor feet were placed in a walking plaster cast for the first postoperative month to facilitate wound healing and to prevent widening of the forefoot. Weight bearing was allowed a week after the operation.

**Figure 2.** An illustration of the donor site after a second-toe transfer. Inclusion of the MTP joint (a) increases the reach of the transfer. However, a more complex recipient site reconstruction is needed to motor and stabilize the MTP joint. A shorter transfer (b) is adequate in more distal reconstructions. This leaves the metatarsal arch intact.

**Figure 3.** An illustration of the donor site after a double en-block transfer of the second and third toes. This transfer is used for reconstruction of adjacent fingers. The MTP joint of either or both toes can be included in the transfer.

**Study protocol**

Patient charts were carefully evaluated and information about the reconstructive operation and postoperative period, including complications and secondary operations, was recorded. The follow-up visit consisted of radiographic and clinical evaluation of the donor site. The patient-reported, clinician-based, functional and radiographic outcomes were evaluated separately.

The functional outcome (activities of daily living [ADL]), pain and neuropathic symptoms were addressed by a 15-question questionnaire (designed by the authors for the microvascular toe transfer patients) that the patients filled out during the
evaluation visit. Patients were asked to rate their answers into four categories that equalled one to four points. No complaint gave four points, minor complaint three, moderate complaint two and major complaint gave one point. From the ADL-section of the questionnaire (seven questions), a score ranging from 7 to 28 points was calculated. The more points the better the result.

An AOFAS (American Orthopedic Foot and Ankle Society) scale for hallux metatarsophalangeal-interphalangeal disorders was chosen because problems of this area, especially hallux valgus deformity, can be anticipated after toe transfers (Kitaoka et al., 1994). It was translated into Finnish and used to evaluate the patients. This clinical rating system is divided into pain (40 points), function (45 points) and alignment (15 points). It has a range of 0–100 points, but does not translate the received result into a verbal category. For the purposes of this study, we set the limit of a good result at 78 points, which can be achieved when there is at most mild, occasional pain, no limitation of daily or recreational activities, no footwear limitations, only moderate restriction of MTP joint motion, full range of interphalangeal (IP) joint motion, no MTP-IP joint instability, no symptomatic callus and at least fair alignment of the hallux.

Both feet were radiographed with the patient standing up. Osteoarthritis according to Gahunia et al. (1995) of the first MTP joint, hallux valgus angle (HVA), the width of the forefoot and quality of bone in terms of osteopenia were evaluated (Figure 4(a)). Further, the angles between the first and the second metatarsus (intermetatarsal angle (IMA) I–II) and the first and the third metatarsus (IMA I–III) were measured. That is, IMA I–II of the donor feet could only be measured when adequate length of the second metatarsus was left (n = 53). The radiographic grading of the severity of hallux valgus deformity was defined as follows: normal [HVA <15°, IMA I–II <9°], mild [HVA 16–20°, IMA I–II 9–11°], moderate [HVA 20–40°, IMA I–II 11–16°] and severe [HVA >40°, IMA I–II >16°] (Coughlin, 1996). The unaffected foot acted as a control in cases of unilateral transfers. A radiologist, who had not taken part in the care of the patients, examined all the radiographs.

Analysis of the data

Categorical variables were reported as frequencies and percentages, and were tested with Fisher’s exact test. Due to skewed distributions, continuous variables were expressed as medians and ranges and tested by the Mann–Whitney non-parametric test. Spearman’s
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The median and (range) of follow-up for the 74 patients were 16 years 7 months (31–358 months) and for the 80 feet 16 years 4 months (11–358 months). No statistical testing was done between the results of outcomes of different transfer groups (great toe, third toe, single second toe, double en-block second and third toes and double second toes) due to the small number of patients. Certain important results are presented in Table 2.

**Table 2.** Patient-reported and functional outcomes of the three major transfer groups.

<table>
<thead>
<tr>
<th></th>
<th>I toe</th>
<th>II toe</th>
<th>Double en-block</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>n (feet (patients))</td>
<td>5 (5)</td>
<td>68 (64)</td>
<td>5 (5)</td>
<td>78 (74)</td>
</tr>
<tr>
<td>Walking</td>
<td>0</td>
<td>10 (15)</td>
<td>1 (20)</td>
<td>11 (14)</td>
</tr>
<tr>
<td>Running*</td>
<td>2 (40)</td>
<td>11 (16)</td>
<td>1 (20)</td>
<td>14 (18)</td>
</tr>
<tr>
<td>Foot fatiguing</td>
<td>0</td>
<td>7 (10)</td>
<td>2 (40)</td>
<td>9 (12)</td>
</tr>
<tr>
<td>Walking on an uneven ground</td>
<td>2 (40)</td>
<td>9 (13)</td>
<td>1 (20)</td>
<td>12 (15)</td>
</tr>
<tr>
<td>Change in hobbies</td>
<td>0</td>
<td>6 (9)</td>
<td>0</td>
<td>6 (8)</td>
</tr>
<tr>
<td>Pain at rest</td>
<td>0</td>
<td>4 (6)</td>
<td>1 (20)</td>
<td>5 (6)</td>
</tr>
<tr>
<td>Pain during exertion</td>
<td>2 (40)</td>
<td>11 (16)</td>
<td>3 (60)</td>
<td>16 (21)</td>
</tr>
<tr>
<td>Cold intolerance</td>
<td>1 (20)</td>
<td>14 (21)</td>
<td>1 (20)</td>
<td>16 (21)</td>
</tr>
<tr>
<td>General satisfaction</td>
<td>2 (40)</td>
<td>8 (12)</td>
<td>0</td>
<td>10 (13)</td>
</tr>
<tr>
<td>ADL Md (range)*</td>
<td>25 (18–27)</td>
<td>28 (8–28)</td>
<td>23 (17–28)</td>
<td>27 (8–28)</td>
</tr>
<tr>
<td>AOFAS Md (range)</td>
<td>xx</td>
<td>93 (52–100)</td>
<td>78 (55–80)</td>
<td>93 (52–100)</td>
</tr>
</tbody>
</table>

Number (% of patients) reporting major to moderate complaint presented for patient-reported outcomes.

\*n = 67 for the II toe and 77 for total, since one patient with a II-toe transfer was unable to run because of a prosthesis of the contralateral foot.

ADL, activities of daily living; AOFAS, American Orthopedic Foot and Ankle Society; xx, AOFAS scale cannot be measured from patients with a I-toe transfer.

**Results**

The median and (range) of follow-up for the 74 patients were 16 years 7 months (31–358 months) and for the 80 feet 16 years 4 months (11–358 months). No statistical testing was done between the results of outcomes of different transfer groups (great toe, third toe, single second toe, double en-block second and third toes and double second toes) due to the small number of patients. Certain important results are presented in Table 2.

**Patient-reported outcomes**

Most of the patients had only minor complaints concerning the donor site. There were 16 patients who had no complaints concerning the donor foot. Fifteen of them had had a single second-toe transfer and one had had a second toe from one foot and a fourth toe from the other. Neuropathic symptoms (neuroma pain or sensory changes) were at most a minor complaint in the majority (94%–96%) of the feet. Most of the feet with neuropathic symptoms had a single second-toe transfer. Only eight patients were not satisfied with the appearance of the donor foot (six with second- and two with great-toe transfers). Cold intolerance was rated a major complaint in four and moderate in 12 patients/feet. Patients with moderate or severe pain during exertion or foot fatiguing reported less favourable subjective results and scored worse in the functional tests compared with those with no or mild symptoms (Table 3).

**Clinician-based outcomes**

The operation scar was assessed to be constricting in 13 of the 80 feet (16%). This was more common in patients where a hemipulp flap was included with the transfer, 7/19 (37%) compared with 6/56 (11%) without the hemipulp flap. The total active range of motion of the first MTP joint was adequate (>75°) in 54 of the 75 feet with an intact great toe. Twenty feet had some restriction of motion (30–74°) and one was assessed rigid (<30°). Restriction of the first MTP joint motion (<75° versus ≥75°) is associated with a worse result on the AOFAS scale (78 versus 93, respectively, \( p = 0.002 \)). A total of 58% \( (n = 11) \) of patients with the hemipulp included in the transfer had adequate first MTP joint movement, compared with 77% \( (n = 43) \) of those without the hemipulp. The hallux IP joint motion was better preserved, with only three stiff (<10°) joints. The first ray, including IP and MTP joints, was stable in 72 of 75 (96%) feet. Moreover, a symptomatic callus was identified in only seven feet (9% [3 × II-toe, 2 × I-toe and 2 × II–III en-block]).

Fair hallux valgus (some degree of deformity) was present in 38 feet (51%) and 6 feet (8%) had poor obvious symptomatic malalignment of the first ray. That is, in only 31 (41%) feet the first ray was correctly aligned. The first ray alignment, evaluated from donor feet in which the first ray was intact \( (n = 75) \),
was an important indicator of donor site function (Figure 4). The worse the alignment was graded, the more problems the donor feet had with walking ($p = 0.041$), running ($p = 0.002$), foot fatiguing ($p = 0.044$), ADL ($p = 0.042$) and AOFAS scale ($p < 0.001$).

**Functional outcomes**

According to the ADL score, there were 60 feet (76%) with no complaint (25–28 points), 13 (16%) with minor (18–24 points) and four (5%) with moderate complaint (10–17 points). Only two (3%) feet received a score of 8 points, which means that they posed a major complaint (<10 points) for the patient. Further, 62 (83%) of the 75 feet received good (≥78 points) results in the AOFAS scale. Both a good result in the ADL score (>24 points) and on the AOFAS scale (>77 points), predicted good patient-reported outcomes (Table 4). The ADL score and the AOFAS scale had a positive correlation ($\rho = 0.561$, $p < 0.001$).

### Table 3. Patient-reported indicators of donor site defect.

<table>
<thead>
<tr>
<th>Foot fatiguing</th>
<th></th>
<th>Pain during exertion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No or mild</td>
<td>Moderate or severe</td>
</tr>
<tr>
<td></td>
<td>($n = 71$)</td>
<td>($n = 9$)</td>
</tr>
<tr>
<td></td>
<td>Md (range)</td>
<td>Md (range)</td>
</tr>
<tr>
<td>Walking on uneven ground</td>
<td>4 [1–4]</td>
<td>1 [1–4]</td>
</tr>
<tr>
<td>Pain during exertion</td>
<td>4 [1–4]</td>
<td>2 [1–3]</td>
</tr>
<tr>
<td>Foot fatigue</td>
<td>xx</td>
<td>xx</td>
</tr>
<tr>
<td>Restriction of hobbies</td>
<td>4 [1–4]</td>
<td>4 [1–4]</td>
</tr>
<tr>
<td>General satisfaction</td>
<td>4 [1–4]</td>
<td>3 [1–4]</td>
</tr>
<tr>
<td>ADL (7–28)</td>
<td>28 (17–28)</td>
<td>15.5 (8–25)</td>
</tr>
<tr>
<td>AOFAS scale (0–100)</td>
<td>93 (55–100)</td>
<td>57 (52–84)</td>
</tr>
</tbody>
</table>

### Table 4. Functional results as predictors of outcome.

<table>
<thead>
<tr>
<th>ADL</th>
<th>AOFAS scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADL ≤ 24 ($n = 19$)</td>
<td>ADL &gt;24 ($n = 60$)</td>
</tr>
<tr>
<td>Md (range)</td>
<td>Md (range)</td>
</tr>
<tr>
<td>Walking</td>
<td>3 [1–4]</td>
</tr>
<tr>
<td>Running</td>
<td>2 [1–4]</td>
</tr>
<tr>
<td>Walking on uneven ground</td>
<td>2 [1–4]</td>
</tr>
<tr>
<td>Foot fatiguing</td>
<td>3 [1–4]</td>
</tr>
<tr>
<td>Restriction of hobbies</td>
<td>4 [1–4]</td>
</tr>
<tr>
<td>Pain at rest</td>
<td>3 [1–4]</td>
</tr>
<tr>
<td>Pain during exertion</td>
<td>2 [1–3]</td>
</tr>
<tr>
<td>Cold intolerance</td>
<td>3 [1–4]</td>
</tr>
<tr>
<td>General satisfaction</td>
<td>3 [1–4]</td>
</tr>
<tr>
<td>ADL (7–28)</td>
<td>xx</td>
</tr>
<tr>
<td>AOFAS scale (0–100)</td>
<td>74 [52–100]</td>
</tr>
</tbody>
</table>

| AOFAS scale ≤ 77 ($n = 13$) | AOFAS scale >77 ($n = 62$) | $P$-value |
| Md (range) | Md (range) | $P$-value |
| Walking | 3 [1–4] | 4 [1–4] | <0.001 |
| Running | 2 [1–4] | 4 [1–4] | <0.001 |
| Walking on uneven ground | 3 [1–4] | 4 [2–4] | <0.001 |
| Foot fatiguing | 3 [1–4] | 4 [2–4] | <0.001 |
| Pain during exertion | 2 [1–4] | 4 [1–4] | <0.001 |
| Cold intolerance | 3 [1–4] | 4 [1–4] | 0.006 |
| General satisfaction | 3 [1–3] | 4 [1–4] | <0.001 |
| ADL (7–28) | xx | xx | xx |
| AOFAS scale (0–100) | 22 [8–28] | 28 [18–28] | <0.001 |

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*a* $n = 79$ for running and ADL since one patient with a II-toe transfer was unable to run because of a prosthesis of the contralateral foot.

ADL, activities of daily living; AOFAS, American Orthopedic Foot and Ankle Society; xx, can not be measured.
Radiographic outcomes

Radiographic assessment was achieved in 73 donor feet and 62 control feet. The results are presented in Table 5. According to the radiographic HVA grading of the donor feet, there were 31 (46%) normal, 14 (21%) mild, 21 (31%) moderate and two (2%) severe. By comparison, the HVA of the control feet was graded as normal in 40 (66%), mild deformity in nine (15%) and moderate in 12 (19%). Of the 18 patients whose control foot had an increased HVA ($\geq 15^\circ$), 17 had the same condition in the donor foot as well, whereas 18 of the 29 patients with increased HVA ($\geq 15^\circ$) of the donor foot had similar grading in the control foot. This accounts to 11 patients (18%) who had an increased HVA only in the donor foot, most likely due to the transfer operation. Further, the HVA was at least 4° greater in the donor than the control feet in 25 patients, which seemed to relate to a worse score on the AOFAS scale (median 78 versus 93, $p = 0.069$) (Figure 5).

Interestingly, both the IMA I–II and IMA I–III were greater in the control compared with the donor feet (median 9° versus 8° and 11° versus 8°, respectively). Concordantly, the forefoot was wider in the control compared with the toe transfer feet (median 80.5° versus 78°).
Complications and secondary operations

In total, 16 patients had problems with healing of the donor site wound. These lead to 11 wound revisions, which were done during an outpatient clinic visit, in eight patients. Additionally, five wounds required a skin graft. Of the patients who had wound healing problems, 62% \((n = 10)\) were smokers, whereas only 38% \((n = 23)\) of patients with uneventful wound healing smoked. Interestingly, almost half of the feet \((6/13)\) where donor wounds were closed with the help of a split-thickness skin graft had wound healing problems. While only 15% \((10/67)\) of directly closed donor wounds had problems in healing, Wound infections were treated with oral antibiotics in eight patients. Patients with wound healing problems scored clinically and statistically worse on the AOFAS scale compared with those without problems \((p = 0.023)\) and seemed to be related to worse scores on the AOFAS scale \((\text{median } 80 \text{ versus } 93, p = 0.065)\). Moderate or severe osteoarthritis was more common among donor \((22\%)\) compared with control \((10\%)\) feet. Moreover, seven \((7/15)\) patients had moderate or severe osteoarthritis only in the operated foot.

Discussion

The purpose of this study was to comprehensively evaluate and report donor site ramifications caused by microvascular transfer of one or two toes. This was achieved by patient-reported, clinician-based and radiographic assessment of the patients and their feet. In addition, we completed two scores (the ADL questionnaire and the AOFAS scale) determining the function of the feet. Even though our patient material was heterogenic, we were able to differentiate certain subgroups of patients and discuss their role in light of the expected result of toe transfer operation. In addition, we were able to link some of the patient-reported, clinician-based and radiological outcomes to anticipated functional outcome. The patient population consisted mainly of adults and the small number of patients at growing age does not allow conclusions about effects of growth to the donor site.

Influence of the transfer on the outcome

Metatarsal length. The length of the second metatarsus included in the single toe transfer had no effect on donor site outcome. There were 58 patients who had a single second-toe transferred. Of those, the second metatarsal was left at normal length in 36 patients, and for the rest \((22\%)\) it was either short or absent. Contrary to Gu et al. \((1997)\), we found no significant difference in any of the patient-reported or clinician-based parameters or the AOFAS scale between the two groups. Further, patient satisfaction was similar.

Inclusion of the hemipulp flap in the transfer. The hemipulp flap from the fibular side of the great toe was related to more scar constriction and restricted first MTP joint motion. The alignment of the first ray was, however, not affected.

Influence of the number of nerves harvested. The majority \((69\text{ out of } 80)\) of the toe transfers were harvested with one or more dorsal, in addition to plantar, nerves. This did not increase donor site morbidity.

Selection of the type of the toe transfer. The patient-reported and functional results seem generally better in the second toe transfer group compared with...
great toe or double en-block transfer groups (Table 2). All but one of the patients who had no complaints concerning the donor foot had had a single second-toe transfer. These findings cannot, however, be verified statistically due to the group sizes being too small. Similarly, Chung and Wei (2000) noticed a statistically insignificant superiority of second-toe over small. Similarly, Chung and Wei (2000) noticed a statistically due to the group sizes being too small. These findings cannot, however, be verified functionally between toe transfer patients and controls. Yang and Gu (2000) stated that 86% of their toe transfer patients had recovered normal donor foot function within 6 months. Our results are quite comparable with those of Yang and Gu’s. A total of 83% of our patients scored well on the AOFAS scale and 76% reported no complaint on the ADL questionnaire. Further, patients who received a good score (>77 points) on the AOFAS scale (n = 62) reported better results in all the patient-reported outcomes when compared with those who scored worse (n = 13). Similarly, they scored better on the ADL questionnaire (median 28 versus 22), and had more often a normal alignment of the first ray (48 versus 8%).

Radiographical outcomes

Osteopenia is rare after toe transfer operation. Contrary to Tiamfook et al. (1994), who found at least some form of osteopenia in 11/15 patients with great toes transferred, we documented mild osteopenia in only five out of 73 operated and in four out of 62 control feet. The osteopenia was bilateral in four out of five patients. The variance between their and our results may be due to different follow-up times and the different transfers used. There is an increased risk of developing a hallux valgus deformity after toe transfer operation. Eleven (18%) of our patients with a single second-toe transfer displayed pathologically increased HVA (>15°) in the donor but not in the control foot. In addition, there were 25 patients who had at least 4° greater HVA in the operated compared with the control feet, which seemed to be related to a worse score on the AOFAS scale. Our results are comparable with those of Beyaert et al. (2003), even though their patients were all children. According to the Coughlin (1996) HVA severity grading there were 21 (31%) feet with moderate and two with severe hallux valgus deformities. These patients did not report inferior patient-reported outcomes compared with those with no or mild hallux valgus deformity. However, they scored worse on the AOFAS scale (median 78 versus 93).

The IMA I–II can be considered even more relevant than the HVA in estimating the deformity and the alignment of the forefoot in dysfunction. This angle has not been reported previously in toe transfer patients. The results of our study show that there is no marked increase of the IMA I–II or the forefoot width in feet where toes were transferred compared with their controls. It may be that a scar, formed in

Patient-reported outcomes

The transfer of single or double toes affects the perceived function of the donor site although satisfaction remains high. Yang and Gu (2000) reported minor problems in 17 out of 86 patients who had had either a second toe, multiple toe or an MTP joint transfer. Further, they report that 86% of the donor feet had fully recovered from the operation in six months and those patients were very satisfied. Contrary to their results, only 16 of our patients were symptom free. Yet, 88% of our patients were satisfied with the donor foot.

Clinician-reported outcomes

Maintaining the alignment of the first ray is important for the function of the foot. Yang and Gu (2000) reported 13 (four of which were hallux valgus) deformities within 84 patients with different types of toe transfers. Gu et al. (1997) reported deformity rates of 10%–13% (second-toe transfer) and 42% (double-toe transfer) in 84 patients without specifying the type or severity of the deformity. We evaluated the alignment of the first ray while the patient was standing. This revealed that in only 31 (41%) of the 75 feet the alignment was correct. The first ray malalignment was linked to worse functional result. Toe transfer (other than the great toe) limits active motion of the first MTP joint. In 21 of the 75 feet in our study, it was restricted at least moderately. This did not reflect to walking, running or pain, but patients with restricted first MTP joint active motion scored worse on the AOFAS scale when compared with those with normal motion (median 78 versus 93, respectively, p = 0.002). The restricted first MTP joint active motion can be an independent nominator for inferior results (according to the AOFAS scale), but it also reflects the fact that these patients had also more first MTP joint osteoarthritis and more often a pathologically increased HVA.

Functional outcomes

The functional outcomes of the donor foot are generally good in patients with toe transfers. Chung and Wei (2000) used a Lower Limb Functional Questionnaire to evaluate the function of toe transfer (n = 16) and control (n = 6) patients. They did not find a significant difference of function between toe transfer patients and controls. Yang and Gu (2000) stated that 86% of their toe transfer patients had recovered normal donor foot function within 6 months. Our results are quite comparable with those of Yang and Gu’s. A total of 83% of our patients scored well on the AOFAS scale and 76% reported no complaint on the ADL questionnaire. Further, patients who received a good score (>77 points) on the AOFAS scale (n = 62) reported better results in all the patient-reported outcomes when compared with those who scored worse (n = 13). Similarly, they scored better on the ADL questionnaire (median 28 versus 22), and had more often a normal alignment of the first ray (48 versus 8%).

Osteopenia is rare after toe transfer operation. Contrary to Tiamfook et al. (1994), who found at least some form of osteopenia in 11/15 patients with great toes transferred, we documented mild osteopenia in only five out of 73 operated and in four out of 62 control feet. The osteopenia was bilateral in four out of five patients. The variance between their and our results may be due to different follow-up times and the different transfers used.

There is an increased risk of developing a hallux valgus deformity after toe transfer operation. Eleven (18%) of our patients with a single second-toe transfer displayed pathologically increased HVA (>15°) in the donor but not in the control foot. In addition, there were 25 patients who had at least 4° greater HVA in the operated compared with the control feet, which seemed to be related to a worse score on the AOFAS scale. Our results are comparable with those of Beyaert et al. (2003), even though their patients were all children. According to the Coughlin (1996) HVA severity grading there were 21 (31%) feet with moderate and two with severe hallux valgus deformities. These patients did not report inferior patient-reported outcomes compared with those with no or mild hallux valgus deformity. However, they scored worse on the AOFAS scale (median 78 versus 93).

The IMA I–II can be considered even more relevant than the HVA in estimating the deformity and the alignment of the forefoot in dysfunction. This angle has not been reported previously in toe transfer patients. The results of our study show that there is no marked increase of the IMA I–II or the forefoot width in feet where toes were transferred compared with their controls. It may be that a scar, formed in
the operation site, prevents the forefoot from widening. The 11 patients with moderate hallux valgus deformity of the donor feet (IMA I–II 11°–16°) did not show any difference in any of the patient-reported functional outcomes compared with those 42 patients with IMA <11°.

The presence of moderate to severe osteoarthritis did not translate to increased pain (at rest or during exertion); however, it seemed to influence the first ray alignment and function of the donor foot. The toe transfer operation increases the risk of osteoarthritis, but it is also age related.

**Donor site wound healing**

Problems early on in the recovery period continue to cause trouble even years after. The 16 patients with donor site wound healing problems scored worse on the AOFAS scale, had more scar problems and experienced difficulties in walking. Restriction of smoking, planning the transfer to enable direct wound closure and a postoperative protocol to minimize the risk of wound healing problems are definitely needed. Interestingly, of the four patients with arteria dorsalis pedis (long pedicle) included in the transfer, three had problems with donor site wound healing. Resection of this artery may diminish the remaining circulation of the foot to the extent to cause wound healing problems.

Our study is retrospective and therefore information about the pre-study period is subject to flaws. Because the pre-operative assessment of patients’ feet was not available, we can only estimate the effect of the transfer operation on the feet. The use of the other foot as a control is controversial. That is, changes in the donor foot may influence the control foot as well. Our follow-up can be considered long-term, even though there is one foot/transfer that has only 11 months of follow-up. Further, there may be a bias in our patient population; 74 (80 feet) of the 97 patients (101 feet) attended the follow-up. This can still be regarded as an acceptable response (76%) considering the long time elapsed from the reconstruction to the commencement of the study and the fact that these patients are spread all around the country. We report a heterogenic patient population that has had many types of transfers harvested. Further, the number of patients in different transfer groups is too small to enable comparison between the groups.

In conclusion, we can state that transferring one or two toes has a definite effect on the donor site. That is, both patient-reported and functional symptoms should be expected. For that reason, the decision to transfer a toe must be balanced between the achievable gain in the function of the hand and the anticipated defect of the foot. The donor site defect is in most cases of minor inconvenience and patient satisfaction is still at a high level.

**Conflict of interests**

None declared.

**Ethical approval**

This study has been approved by the Ethical Committee of Tampere University Hospital. Informed consent: all the patients attending this study signed an informed consent form.

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**References**


