Surgical Restoration of Grasp Control in Tetraplegia

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Cover illustration: One of the patients using his grasp and release function after the alphabet procedure.

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To my family

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ABSTRACT

Aim: The overall aim of this thesis was to improve the grasp and release function of patients with tetraplegia undergoing reconstructive hand surgery. In order to reach this objective, new and more cost-efficient surgical concepts with maintained patient safety were designed.

Patients and methods: 112 individuals were assessed pre- and postoperatively on their pinch and grip strength, range of motion (ROM), hand opening , as well as a satisfactory score (COPM) (retrospective comparative studies I-IV) and dynamic electro-goniometry to assess spasticity (prospective pilot study V).

Results: I: Selective release of tight interossei muscles in the hand (distal ulnar intrinsic release) increased the ROM up to 45 %. **II**: The alphabet procedure (a single-stage combination of procedures) reliably provided tetraplegic patients with pinch, grasp and release function after only one operation and one rehabilitation period. **III**: The extensor carpi ulnaris tenodesis corrected radial deviation deformity of the wrist joint and increased the grip strength by double. **IV**: Patients who underwent the alphabet procedure demonstrated significantly more grip strength and opening of the hand compared with patients, who had traditional grip reconstruction. Early active rehabilitation was particularly important after multiple simultaneous procedures. **V**: Dynamic electro-goniometry proved a feasible method to assess spasticity-reducing surgery by measuring joint angular velocity and repetitions per second. Together with COPM, these assessment points can be used to evaluate the outcome of surgery or non-operative spasticity treatments.

Conclusion: This thesis reports development and refinement of several surgical techniques that individually and combined, facilitate the reanimation of grasp control in people with tetraplegia. Rebalancing of the hand by selective release and tendon lengthening techniques enables more favorable mechanical conditions for the forearm, wrist and finger actuators in patients with tightness and spasticity. Shorter total time in the operation room and for rehabilitation with preserved patient safety enforce the recommendation of applying these techniques.

Keywords: alphabet procedure, distal intrinsic release, ECU-tenodesis, grasp and release, grip strength, intrinsic tightness, opening of the 1st web space, pinch strength, tendon transfer, tetraplegia
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SAMMANFATTNING PÅ SVENSKA

Avhandlingen handlar om utveckling av olika kirurgiska metoder som förbättrar både gripförmåga och öppning av handen hos patienter med totalförlamning och spasticitet efter halsryggmärgsskada. Sedan tidigare finns bra metoder, flyttning av fungerande muskler (sentransfereringar) för att rekonstruera armbågssträckning, handledssträckning, tumböjning och fingerböjning. Bättre öppning av handen har bara ett fåtal patienter kunnat få förut. Totalt har 112 ryggmärgsskadade personer ingått i studierna, där greppstyrka, öppning av handen, rörlighet och patientnöjdhet (COPM) mätts före och efter operation. Selektiv lossning av strama handmuskler (distal ulnar intrinsic release) för att få bättre rörlighet och bättre greppkontroll ger upp till 45 % bättre rörlighet i knoglederna. ECU-tenodes (upprätning/ balansering av handleden) gav dubbla greppstyrkan jämfört med en grupp som opererades på traditionellt sätt. En ny kirurgisk metod har utvecklats för att rekonstruera tum-, helhandgrepp samt öppning av handen i en och samma operation (i stället för två): alfabetoperation. Resultaten visar att patienterna får dubbelt så hög greppstyrka och bättre öppning av handen jämfört med tidigare grepprekonstruktioner. Patientnöjdheten är kliniskt relevant; hög. En ny metod, dynamisk elektrogoniometri, digital mätning av ledrörlighet, har testats för utvärdering av spasticitetslindrande operationer. Metoden är lovande och kan användas vid större studier av behandling av spasticitet.

Slutsats: Denna avhandling visar att vidareutvecklade och förfinade kirurgiska metoder, var för sig eller i kombination, underlättar greppkontroll hos patienter med ryggmärgsskada och totalförlamning. Selektiv lossning av muskler och senförlängningar möjliggör gynnsammare mekaniska förhållanden i underarm och hand hos patienter med stramhet och spasticitet. Studien visar att det går att kombinera flera operationer samtidigt på ett patientsäkert och kostnadseffektivt sätt.

LIST OF PAPERS

This thesis is based on the following studies, referred to in the text by their Roman numerals.

I. Reinholdt C, Fridén J. Selective release of the digital extensor hood to reduce intrinsic tightness in tetraplegia. J Plast Surg Hand Surg 2011; 45: 83-89.

II. Fridén J, Reinholdt C, Turcsányii I, Gohritz A. A single-stage operation for reconstruction of hand flexion, extension, and intrinsic function in tetraplegia: The Alphabet procedure. Tech Hand Up Extrem Surg 2011; 15: 230-235.

III. Reinholdt C, Fridén J. Rebalancing the tetraplegic wrist using extensor carpi ulnaris-tenodesis. J Hand Surg Eur 2013; 38: 22-28.

IV. Reinholdt C, Fridén J. Outcomes of the alphabet procedure for grip reconstruction in tetraplegia. Manuscript.

V. Reinholdt C, Fridén J. Alteration of finger and wrist flexor kinematics after surgical intervention on the spastic hand in tetraplegia. Manuscript.

CONTENTS

ABBREVIATIONS

AdP	Adductor Pollicis
APB	Abductor Pollicis Brevis
BR	Brachioradialis
CMC	Carpometacarpal joint
COPM	Canadian Occupational Performance Measure
ECRB	Extensor Carpi Radialis Brevis
ECRL	Extensor Carpi Radialis Longus
ECU	Extensor Carpi Ulnaris
EDC	Extensor Digitorum Communis
EDM	Extensor Digiti Minimi
EIP	Extensor Indicis Proprius
EPL	Extensor Pollicis Longus
FCR	Flexor Carpi Radialis
FDP	Flexor Digitorum Profundus
FDS	Flexor Digitorum Superficialis
FPL	Flexor Pollicis Longus
ICSHT	International Classification for Surgery of the Hand in Tetraplegia
IP	Interphalangeal joint
MCP	Metacarpophalangeal joint
OCu	Ocular Cutaneous
PIP	Proximal Interphalangeal joint
PT	Pronator Teres
ROM	Range Of Motion
SCI	Spinal Cord Injury

DEFINITIONS IN SHORT

Muscle release	Surgical detachment of one end of a muscle, usually at the insertion site
Paralysis	Impairment or loss of voluntary muscle function, usually as a result of neurologic injury or disease
Paresis	Incomplete paralysis
Pinch	Squeezing of the end of the thumb to the end of one or more fingers
Spasticity	Increased muscle tone, or stiffness, causing continuous resistance to stretching
Spasticity-reducing surgery	Tendon lengthening and/ or muscle release to relax the muscle-tendon unit in order to reduce spasticity
Tendon transfer	The moving of one tendon to another to restore a function
Tenodesis	The surgical anchoring of a tendon , as to a bone
Tetraparesis	See below, paresis means incomplete paralysis, the patient has some residual functions left below the injury level
Tetraplegia	Tetra = 4 in Greek, plegia means complete paralysis, the patient is paralyzed below the injury level

1 INTRODUCTION

Suffering a spinal cord injury causes a huge life transition in, where simple everyday tasks become a challenge. In addition to a broad paralysis and numbness, there will also be functional disturbances of urination, defecation, sexual function and pain problems, as well as spasticity and pressure sores problems. There is no treatment today that can cure spinal cord injuries (SCI), but highly specialized care can rehabilitate and partially reconstruct some of the damaged functions. The aim is to achieve as high a degree of autonomy as possible. When asked which function they would most like to regain, people with tetraplegia rank hand and arm control as the most important (Anderson, 2004). Patients with tetraplegia due to SCI often benefit greatly from grip reconstruction which improves hand function. At the international congress of tetraplegia hand surgery and rehabilitation in Philadelphia in 2007, a resolution was established. The resolution states that every person who sustains a spinal cord injury with tetraplegia should be examined, assessed and informed about possible reconstruction of motor function in their upper extremities (Fridén & Reinholdt, 2008).

Hands are like the face in the sense that they are always visible and very personal. It is the patient´s interface with the world and an emblem of strength, skill, sexuality, and sensibility (Brand & Hollister, 1999). When the hands are damaged, it becomes a symbol of the vulnerability of the whole person. Reconstruction of the grip or key grip has been possible for many patients with tetraplegia for several decades. Reconstruction aimed at opening the hand is not always performed; however, without adequate opening, the patient is unable to fully use the reconstructed grip. Patients with spasticity often suffer from the inability of voluntary opening of the hand. An open hand is socially important. It enables an individual to greet others, shake hands, and to use a computer mouse to be able to interact in social media-wishes that are often expressed. More seldom the patients pronounce their wishes of being able to feel, caress, grab, squeeze, and hug, which also require open hands (Figure 1). Opening of the hand can be managed in two ways: reconstruction or by spasticity-reducing procedures. Opening of the hand and grip control are the main themes running through this thesis. A new procedure of grip reconstruction: the alphabet procedure and its outcomes will be explained. The alphabet procedure combines reconstruction of flexion and opening of the hand in a single-stage procedure. Tenodesis of the extensor carpi ulnaris (ECU) corrects wrist radial deviation deformity, which is common among patients with tetraplegia: correcting this deformity results in a stronger grip, and probably a more ergonomic position of the arm for gripping. Distal ulnar intrinsic release is useful to regain better range of motion (ROM) in proximal interphalangeal (PIP) joints and better grip control in patients with or without spasticity. A third of all the procedures performed at our unit are spasticity-reducing. To assess these pre- and postoperatively a new method: Biometrics with electro-goniometers has been tested.

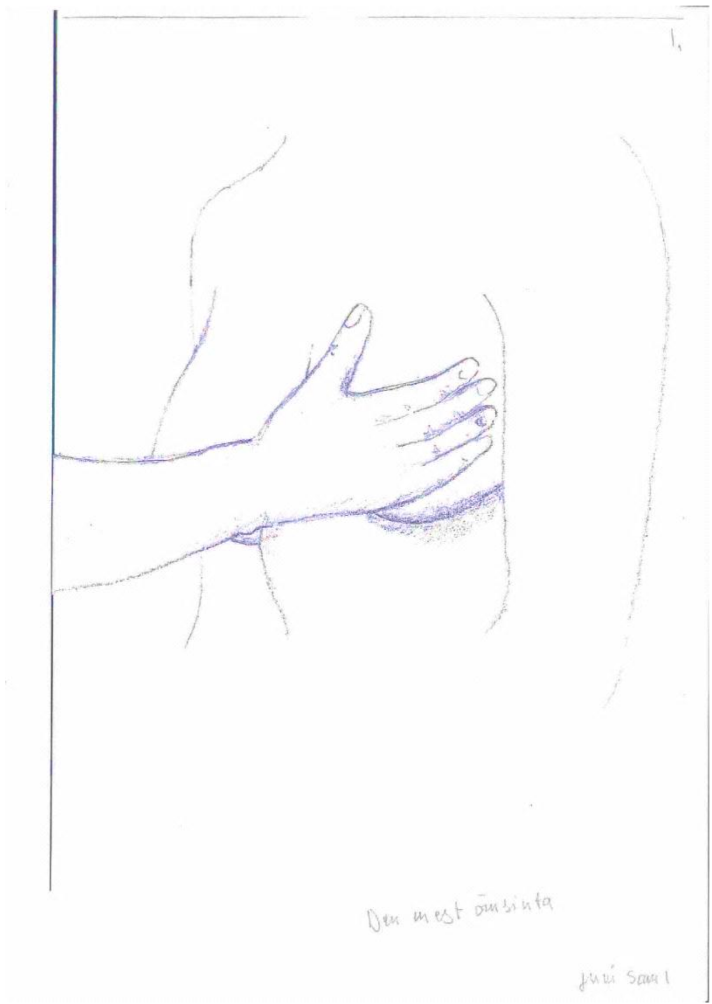


Figure 1. "Den mest ömsinta" by Anna-Maria Edgren.

1.1 Epidemiology

In Sweden, spinal cord injuries (SCI) have an annual incidence estimated at 10-15 new cases per million people: 55% of these occur in the cervical region, due to the high anatomical mobility. The most common cause is motor vehicle accidents (40-50%). The prevalence in Sweden is 5000 people. The average age at injury is 31 years and 80% are males. The life expectancy has increased over the last few years and is not far from normal (Holtz & Levi, 2006). The incidence of incomplete SCI has increased over the last few years and has been reported up to 67% (Maynard, 1990) and 78% (Sköld et al, 1999). This is thought to be due to better emergency care and safer cars. The most common level of cervical SCI is at the C5-7 level (Hentz & Leclercq, 2002).

1.2 Historical Review

Modern rehabilitation of spinal cord injuries started in 1944 at the Stoke-Mandeville National Spinal Centre in England, by the neurosurgeon Sir Ludwig Guttmann (Holtz & Levi, 2006). Before 1940, most patients with spinal cord injuries died within 14 days. Modern rehabilitation requires the cooperation of several specialties such as intensive care and pain management, neurosurgery, orthopedics, urology, and hand surgery. When the survival rate increased, the need for reconstruction of the arms and hands evolved. In 1948 Sterling Bunnell published advancements in the tendon transfer surgery for cervical SCI (Bunnell, 1948). Lipscomb et al developed a two-stage surgical grasp and release in 1958 (Lipscomb et al, 1958). Freehafer described the transfer of brachioradialis to wrist extension in 1967 (Freehafer & Mast, 1967). Lamb and Zancolli brought grip reconstruction techniques forward in the 70´s (Lamb & Landry 1971, Zancolli 1968, 1975). Moberg presented the need for elbow extension reconstruction with posterior deltoid to triceps transfer combined with a single-stage pinch tenodesis in 1975 (Moberg, 1975). Moberg also presented the first classification system based on sensibility and grade 4 muscles in 1978 (Moberg, 1978), which was the same year that the first international congress for surgical rehabilitation of upper limbs in tetraplegia was held (in Edinburgh). In 1984 the classification was modified to what it is in modern day (McDowell et al, 1986). Hentz, Allieu, Brys, Waters, and House contributed to the further development and knowledge of assessment, tendon transfers, tenodeses and arthrodeses during the 80´s (Hentz, 1983, Waters et al, 1985, House & Shannon, 1985, Allieu et al, 1986, Brys & Waters, 1987). McCarthy and House have further developed intrinsic reconstruction (1997). Ejeskär has refined the restoration and rehabilitation of elbow extension (Fridén and Ejeskär et al, 2000).

1.3 Pathogenesis

The cervical spine has 7 vertebrae and their ligaments, which are divided into eight segments, are prone to injury due to their wide range of motion. Encased in the seven vertebrae is the cervical spinal cord. A trauma to the cervical spine, which consists of several mechanisms, can each lead to functional loss (Holtz & Levi, 2006). For instance: in a fraction of a second a fractured vertebrae or a dislocated segment can compress the spinal cord, followed by the remaining pressure being applied to the spinal cord caused by bone fragments, disc material, and blood. Contusion injuries are the most common. Edema and injured microcirculation may cause further secondary injuries.

The cervical spinal cord can sustain complete or incomplete injury at the level of trauma. If the injury is incomplete, residual functions below the trauma level will be present. Tetraparesis is another definition of incomplete injuries. Traditionally, however, probably because complete injuries were more common, patients with cervical SCI are defined with tetraplegia, even though they may have an incomplete injury.

1.4 Classification

The American Spinal Injury Association (ASIA) has developed a classification to describe the neurological level of injury and the sensorimotor function above and below the level of injury. Examination according to ASIA gives only parts of the relevant information, however, and must be followed by a complete physical status (Holtz & Levi, 2006). The ASIA Impairment Scale, which is part of the classification, grades residual function below the level of injury in 5 grades from A-E. ASIA grade A is a complete injury and E has voluntary motor and sensory function (Holtz & Levi, 2006). The ASIA classification is, however, not very useful from a reconstructive view, when more specific information of motor function is needed.

The International classification for surgery of the hand in tetraplegia (ICSHT) (McDowell et al, 1986) is instead more helpful for reconstructive planning (Table 1). In this classification, all muscles below the elbow with a muscle grade of at least 4 are counted (see subchapter 3.4.4, Table 3). For planning reconstructive surgery that information is more useful.

Table 1. International Classification for Surgery of the Hand in Tetraplegia (ICSHT)

Sensibility	Motor	Characteristics	Function
O/Cu	0	No muscle (M4) below elbow	Elbow flexion
O/Cu	1	BR	Elbow flexion
O/Cu	2	ECRL	Extension of the wrist (weak)
O/Cu	3	ECRB	Extension of the wrist (strong)
O/Cu	4	PT	Pronation
O/Cu	5	FCR	Flexion of the wrist
O/Cu	6	Finger extensors	Extension of the fingers
O/Cu	7	Thumb extensor	Extension of the thumb
O/Cu	8	Partial digital flexors	Flexion of the fingers (extrinsic)
O/Cu	9	Lacks only intrinsics	Flexion of the fingers
O/Cu	X	Exceptions	

1.5 Preoperative Planning

A patient-focused view is the basis of the preoperative planning. It is important that the patient describes their needs and expectations of surgery. Expectations have to be realistic and the patient must be motivated to carry out the rehabilitation to meet those needs. Thorough information and sometimes several visits to the out-patient clinic are necessary. Meeting other patients who have undergone the surgery is also sometimes useful. Special needs during rehabilitation need to be planned, such as extra assistance, electric wheel chair, and lifts. For the surgeon it is important to assess muscle function before operating (Table 3) to decide what functions can be restored. Functions that need to be considered for reconstruction are: elbow extension, wrist extension, finger flexion, thumb flexion and opening of the hand. Candidates for surgery are patients whose injury occurred at least 12 months ago, who have a stabilized motor recovery and are medically stable (blood pressure, bowel, bladder function, and infection free) (Wolfe et al, 2011). Further neurological recovery must be ruled out and no further improvement with rehabilitation can be obtained. The patient must have adapted to his or her new environment and life situation. Usually this adaptation takes a year, sometimes longer. The patients´ personal preferences should be taken into account when timing the surgery. Surgery will increase their independence, but the patient will still remain functionally impaired. According to recent literature contraindications are spasticity, contractures, chronic pain problems and psychological instability (Wolfe et al, 2011). Spasticity is often reduced conservatively and some patients are good candidates for spasticity-reducing surgery. Contractures should be treated with splints. A good passive ROM of finger joints should already be maintained from the acute phase of the injury: while this is a prerequisite for good surgical outcomes of grip reconstruction. Chronic pain is, however, not a contraindication since many of the patients treated at our unit have chronic pain and do well regardless. Pain is likely to be worse during the acute phase and the rehabilitation period, so extra pain management care is needed. This issue must be thoroughly discussed with the patient preoperatively. In fact, better function that allows more mobility and activity may be helpful in the treatment of chronic pain.

1.6 Principles of Tendon Transfers

Tendon transfer means relocation of a donor muscle to a different (recipient) site (tendon or bone) in order to achieve or augment a lost function (Fridén, 2005). During World War I, tendon transfer surgery was developed. Many of the general principles of tendon transfers, which were refined and set by Bunnell and Littler, still apply (Bunnell, 1948, Littler, 1949). The donor muscle must have a muscle strength grade of M4 at least (Table 3) (Bunnell, 1948). Matching the donor muscle with the right recipient muscle, based on muscle architecture is important. Lieber and Brown (1992) presented an index to facilitate the matching of muscles based on architectural properties (physiological cross-sectional area, fiber bundle length, muscle length, muscle mass, and pennation angle). In patients with tetraplegia there are not many expendable muscles appropriate for tendon transfer. Contractures have to be corrected, preferably with conservative treatment (splints), preoperatively. The condition of the affected joints (passive ROM) must be optimal (Bunnell, 1948). The soft tissues in the operation site have to be in good condition, preferably without scars, burns, infection, edema, and wounds (Steindler, 1919). Transferred tendons should not be placed directly under the skin or skin grafts, or on rough bleeding bone surfaces: as these can lead to adhesions. The transferred tendon should be gently passed through tissue adapted to tendon gliding (Brand, 1988). Irregular bone surface or metal implants may cause ruptures.

The direction of the transferred tendon should have as straight a line of action as possible (Fridén, 2005). The tendon should be adequately mobilized to allow the most direct line of pull. If the route is not straight, a pulley ought to be considered. Another concept is one muscle – one function. This is challenged when brachioradialis (BR) is transferred to the flexor pollicis longus (FPL) dorsally for dual function: pronation and thumb flexion (Fridén, Reinholdt et al, 2012). If the tendon is passed across several joints, several factors may influence the result, such as the moment arm and the direction of pull across each joint (Fridén, 2005).

Another desired concept is to achieve muscle synergism (Littler, 1949) Synergistic muscles contract simultaneously, e.g. digital flexors and wrist extensors. Synergism is considered to help facilitate re-learning and rehabilitation.

Donor site morbidity may occur, and ought to be considered when planning tendon transfers. Harvesting a flexor digitorum superficialis (FDS) tendon, may cause a swan-neck deformity in patients with hypermobile joints, or lead to flexion deformity due to adhesions (Fridén, 2005). Harvesting a useful BR requires an extensive dissection of 12-15 cm to release the strongly tethered tendon (Fridén et al, 2001. Kawakami et al (1994) showed that harvesting the BR includes a loss of 20% in elbow flexor strength.

The setting of the length and tension of a tendon transfer is still controversial. The surgeon will mostly use tactile feel to set the “right” tension. Fridén and Lieber have developed a laser diffraction device, which measures sarcomere length preoperatively (1998). Stress relaxation of a stretched muscle takes 2 minutes, which should be taken into consideration when assessing the tension of a tendon (Einarsson, 2008).

The attachment of the donor and recipient tendons should be done with side-to-side sutures since it is twice as strong as (Brown et al, 2010) the Pulvertaft weave (Pulvertaft, 1948).

1.7 Principles of Tenodeses

Tenodesis is the automatic movement of a joint produced by the motion of another, usually a proximal joint (Hentz & Leclercq, 2002). An example is the natural tenodesis effect: as the wrist extends, the fingers and thumb automatically flex. Reciprocal finger and thumb extension occurs with wrist flexion. A tenodesis procedure involves attaching a tendon to a bone (Zancolli, 1968), ligament or another tendon in order to augment or create some function in paralyzed hands. Tenodesis can be classified as simple (crossing a single joint) or dynamic (crossing more than one joint) (Lipscomb 1958). Two types of dynamic tenodeses can be performed surgically, passive or active tenodeses (Fridén, 2005).

A passive tenodesis is firmly fixed to bone and activates a distal joint through the active motion of a more proximal one (Fridén, 2005). An example of this is the passive key pinch with the FPL attached to the radius. The motion of the wrist controls the “strength” of the pinch. A passive tenodesis is prone to stretching and becoming slack over time.

An active tenodesis is anchored in an active tendon and moves a joint through the action of another functional tendon. An example of this is the split FPL-EPL tenodesis (Mohammed et al, 1992). It is less susceptible to becoming slack and more effective, since it can be actively modulated (Fridén, 2005).

Tenodeses require good passive ROM. Spasticity may reduce the effect of the tenodesis. Active muscles controlling tenodeses should have at least muscle (M4) strength e.g. flexion tenodeses like passive key pinch require wrist extension of good strength. Extension tenodeses, for extension of the fingers or the thumb do not require much strength, and are controlled by wrist flexion, which can be activated by gravitation. Their purpose is to open the hand in preparation to grasp (Fridén, 2005).

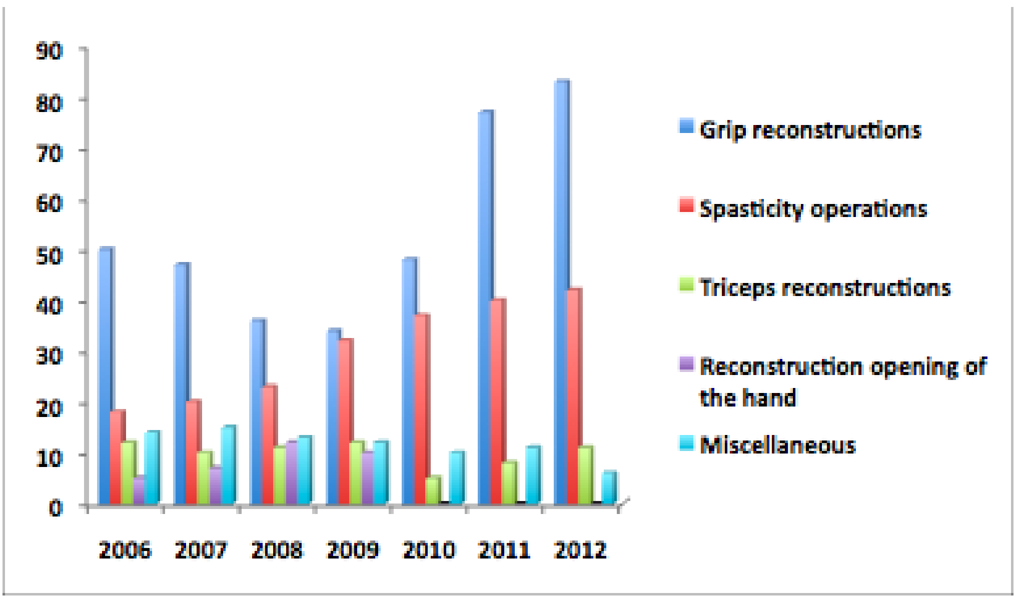
1.8 Spasticity

Patients with spinal cord injury (SCI) have a high probability to develop spasticity: up to 78% of people in groups with traumatic SCI (Sköld et al, 1999). Spasticity is less severe in individuals with complete SCI, and is more severe in those with minimal sparing of functional muscles (Haley & Inacio, 1990).

Spasticity is a velocity-dependent phenomenon, the faster the limb is moved the more resistance it will encounter (Tuzson et al, 2003). Spasticity is defined as a velocity-dependent increase in the stretch reflex (Lance, 1980). The monosynaptic patellar reflex is an example of a stretch reflex. This reflex is important in coordinating normal movements in which muscles are contracted and relaxed. Receptors (muscle spindles) in the muscles receive messages from the nervous system, which then sense the amount of stretch in the muscle and sends that signal to the brain. The brain responds by sending a message back to reverse the stretch by contracting or shortening the muscle. Brain injury or SCI causes changes in the balance of signals between the nervous system and the muscles. This imbalance leads to increased muscle tone and a lack of control of voluntary movements.

There are many conservative treatment methods for spasticity available such as physiotherapy, splints, baclofen, dantrolene, diazepam, clonazepam, botulinum toxin A injections and baclofen pumps. Before surgery is considered conservative treatment ought to be thoroughly explored. Surgical treatment means reducing spasticity by lengthening the tendons, releasing the muscles, and also sometimes correcting deformities. When lengthening a tendon or releasing a muscle from its insertion, the whole muscle-tendon unit is relaxed and becomes less tight. Spasticity is not gone, but reduced in strength. About 1/3 of all surgical procedures performed at our unit are spasticity-reducing procedures (Figure 2).

Figure 2. The number of surgical procedures performed in patients with tetraplegia. The red bar graph represents the spasticity procedures, which have increased over the last few years.



Spasticity can be divided into useful spasticity or harmful spasticity (Allieu, 2002). Harmful spasticity causes contractures, pain, hygienic problems (e.g. clenched fists), transfer problems and involuntary movements. Useful spasticity can be helpful when holding an object or when transferring etc. It also preserves muscle size and bone strength. Spasticity can be triggered by almost anything. An infection, an injury, or a wound will often cause spasticity to increase. In a person who does not perform a regular range of motion exercises, their muscles and joints can become less flexible, and almost any minor stimulation can cause severe spasticity. Spasticity also serves as a warning system when sensation is absent. Increased spasticity may be the signal for a bladder infection.

Spasticity in the hand varies from a completely clenched fist to decreased grip control at triggered spasticity. Some patients have spasticity in all flexor muscles and some only in the intrinsics. Opening of the hand is difficult if the spasticity is ongoing. Gripping and releasing objects requires voluntary control. Intrinsic spasticity is sometimes referred to as tightness or stiffness, which can be due to other causes such as longstanding edema or hematoma, trauma, ischemia, and CNS lesions. When the intrinsic muscles are too tight or spastic, the gripping ability is affected. Small objects and slim tools are difficult to grip onto when flexing of the finger joints is limited by spasticity. If the metacarpophalangeal (MCP) joints are affected, the ability to open the hand is largely reduced.

Methods for measuring and assessing spasticity are debated and the Ashworth scale is considered too subjective according to Fleuren et al (2010). There is no method available to assess spasticity-reducing surgery in a satisfactory way. In study V, a new method using electro-goniometry is tried in a pilot study with 3 assessment points: joint angular velocity (the rate of flexion and extension of a joint), repetitions per second, and Canadian Occupational Performance Measurement (COPM).

2 AIM

The overall aim of this study was to improve grasp and release function in patients with tetraplegia undergoing reconstructive hand surgery.

Specific aims were:

To present a single-stage operation for reconstruction of grip and grasp function (the alphabet procedure).

To develop a new assessment method for spasticity.

To test whether dynamic electro-goniometry can be used to assess spasticity before and after spasticity-reducing surgery.

To evaluate the effect of the distal ulnar intrinsic release procedure to reduce intrinsic tightness, and thereby facilitate grasp function.

To evaluate the specific effects of ECU-tenodesis to rebalance the position of the wrist in order to optimize the mechanical output of the wrist, fingers and thumb actuators.

To evaluate the outcomes of the alphabet procedure compared with the traditional concept of grip reconstruction.

3 PATIENTS AND METHODS

Table 2. Overview of study I-V.

Study	Surgical procedure	Patients/ hands or fingers	Controls	Methods/study design	Statistical analysis
I	Distal ulnar intrinsic release	17/37	-	ROM, Bunnells test/ Retrospective study	One-way ANOVA, Mann-Whitney
II	Alphabet procedure	25/25	-	Key pinch, grip strength/Technical note, /Retrospective study	N/A
III	ECU-tenodesis	18/18	33/43	Grip strength, pinch strength, 1st web space opening/ Retrospective comparative study	Student's T-test, One-way ANOVA
IV	Alphabet procedure	14/16	15/18	Grip strength, pinch strength, 1st web space opening, COPM/ Retrospective comparative study	Student´s T-test, Mann-Whitney nonparametric test
V	Tendon lengthening, muscle release	8/8	-	Electro-goniometry Biometrics, COPM/ Prospective pilot study	ANOVA, Student´s T-test

3.1 Patients

3.1.1 Study I

17 patients with incomplete tetraplegia and intrinsic tightness were divided into 2 groups: mild and severe, depending on the degree of involvement of the MCP joints according to Naidu and Heppenstall (1994). The mild group comprised 7 patients (14 fingers) and the severe group had 10 patients (23 fingers).

3.1.2 Study II

25 patients (25 hands) in three countries underwent the alphabet procedure. The patients belonged to ICSHT groups 3-5. 4 patients were also included in study IV, of whom 1 patient was also included in study III.

3.1.3 Study III

The study group comprised 18 patients (18 hands) in ICSHT classification groups O/Cu 3-X. All patients underwent grip reconstruction with ECU-tenodesis included. 4 patients were also included in study IV, of whom 1 patient was also in study II and IV.

3.1.4 Study IV

The study group comprised 14 patients (16 hands) in classification group OCu 4. All patients had grip reconstructions according to the alphabet procedure. 3 patients were also included in study II, and 3 other in study III. 1 patient was included in both study II and III.

3.1.5 Study V

8 patients (8 hands) with incomplete tetraplegia and spasticity underwent spasticity-reducing surgery. Prior to and 6 months after surgery the patients were assessed with electro-goniometry by Biometrics.

3.2 Control Groups

3.2.1 Study III and IV

Control groups for comparison with the study groups were collected from the Swedish national register for tetraplegia. Inclusion criteria for study III were grip reconstruction without ECU-tenodesis and ICSHT classification group O/Cu 3-X. Inclusion criteria for study IV were ICSHT classification group 4, previous grip reconstruction including BR-FPL, and extensor carpi radialis longus (ECRL) to flexor digitorum profundus (FDP) transfer. In both control groups early active mobilization and a 1 year follow-up were also requested inclusion criteria. 11 of the patients were included in both control groups IV.

3.3 Ethics

Prior to surgery, all patients received oral and written information about details of the procedures, necessary restrictions and the planned rehabilitation protocol. The Regional Ethics Committee of Research Involving Humans in Gothenburg, Sweden approved the studies (Dnr. 101-09).

3.4 Assessment

3.4.1 ROM (Study I-V)

Range of motion (ROM) was measured in all patients in all studies. Finger joints, wrist joints, and elbow joints were always measured preoperatively and at follow-ups after 6 and 12 months. Active ROM is the motion the patient can produce by active flexion or extension of a joint. Passive ROM is when the examiner moves the joint into maximal flexion or extension. In study I passive ROM was measured at 1, 3, and 6 months postoperatively. ROM is measured manually using a goniometer. In study V ROM was measured manually, as well as by electro-goniometers in the DataLink®system (Biometrics, Newport, UK).

3.4.2 Grip Strength (Study II-IV)

Grip strength was measured by using a Jamar Hydraulic Hand Dynamometer (Sammons Preston Inc., Bolingbrook, IL, USA). The result is presented in kilograms. Grip strength was only measured if the patient has the ability to grip. Many patients do not have this prior to surgery.

3.4.3 Opening of the First Web Space (Study III-IV)

Opening of the first web space is the maximum active distance between the thumb and index fingertip measured in centimeters with a plain ruler.

3.4.4 Manual Muscle Testing (Study I-V)

Muscle strength is graded on a 6-point scale, according to the Medical Research Council (MRC, 1943). A muscle with a grade of M4 is considered suitable for transfers (Table 3).

Table 3. Muscle grading according to the Medical Research Council.

Grade	Muscle function
0	Total paralysis
1	Palpable or visible contraction
2	Active movement, full ROM with the help of gravity
3	Full active ROM against gravity
4	Full active ROM against moderate resistance
5	Normal (full active ROM against full resistance)

3.4.5 Key Pinch Strength (Study II-IV)

Key pinch strength was measured by using a Baseline Mechanical Pinch Gauge (Fabrication Enterprises Inc., White Plains, NY, USA). The result is measured in kilograms.

3.4.6 Bunnell´s Test (Study I)

Bunnell´s test (Bunnell et al, 1948) is commonly used by hand surgeons when diagnosing intrinsic tightness of the PIP joints. Finochietto has also described the test (Finochietto, 1920). Bunnell´s intrinsic tightness test involves passively holding the patient´s MCP joint extended, and then passively flexing the PIP joint. There is intrinsic tightness if the PIP joint is difficult to flex (Fig. 1 in Study I). The test can also be used to distinguish between intrinsic tightness on the ulnar or the radial sides. With the MCP joint in a maximally-deviated position to the radial and ulnar side respectively, the test can determine the radial and ulnar intrinsic insertions for tightness.

3.4.7 COPM (Study IV-V)

Canadian Occupational Performance Measure (COPM) (Law et al, 1998) was used prior to and 6 months after surgery on patients in study IV-V. COPM is an assessment tool with a score system from 1-10, based on the patient´s interview and feedback. The patients select 5 rehabilitation goals, and score them from 1-10 based on performance and satisfaction. At follow-up self-scoring of the same goals is done. An increase of 2 points is considered a relevant clinical difference (Carswell et al, 2004). The COPM was recommended for tetraplegia research by consensus at the 8th Tetraplegia meeting in 2004 (Bryden et al, 2005). The COPM interviews are performed by the occupational therapist of the tetra-hand surgery team.

3.4.8 Spasticity (Study I and V)

Patients in study I with spasticity and intrinsic tightness were assessed with ROM and Bunnell´s test. Patients in study V were assessed manually regarding to their ROM, grip strength, pinch strength, and COPM.

3.4.9 Dynamic Electro-goniometry (Study V)

Electro-goniometers (Electro-goniometry DataLINK by Biometrics) were placed dorsally over the joint to be measured (the pip-joints and the wrist in study V). ROM over time is instantly presented as graphical data on the connected computer. Joint angular velocity (º/s) and repetitions/second are calculated and visible in the analysis program (Figure 3).

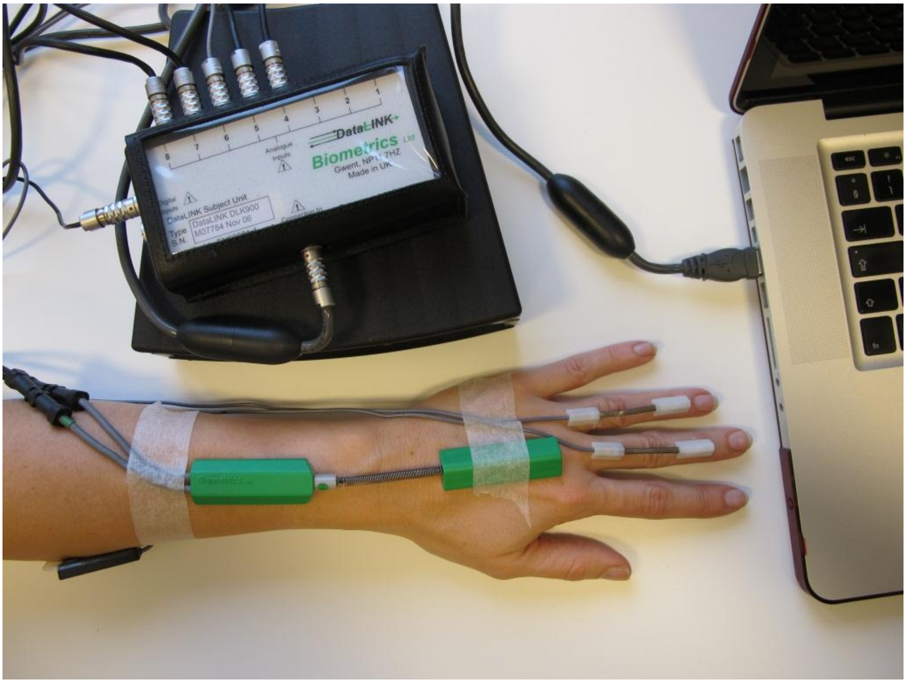


Figure 3. The set-up of the method in study V.

3.5 Surgical Techniques

3.5.1 BR-FPL Tendon Transfer (Study II and IV)

The brachioradialis (BR) is released from its insertion in the radial styloid. There are numerous strong fascial connections and the tendon need to be released at least 12-15 cm (Fridén et al, 2001). The radial nerve passes under the tendon and needs to be protected. The radial artery is parallel to the BR tendon. The muscle must be released proximally until the passive amplitude is at least 3 cm (in vitro studies). The BR has a fiber length of 12 cm that theoretically would allow for excursions up to 6 cm (Fridén et al 2001). The

BR tendon is passed through the FPL tendon once and then sutured with a test suture. The tension is correct when the thumb rests against the index finger with light tension while the elbow is flexed 90º. The tendons are attached with side-to-side sutures (Figure 4).

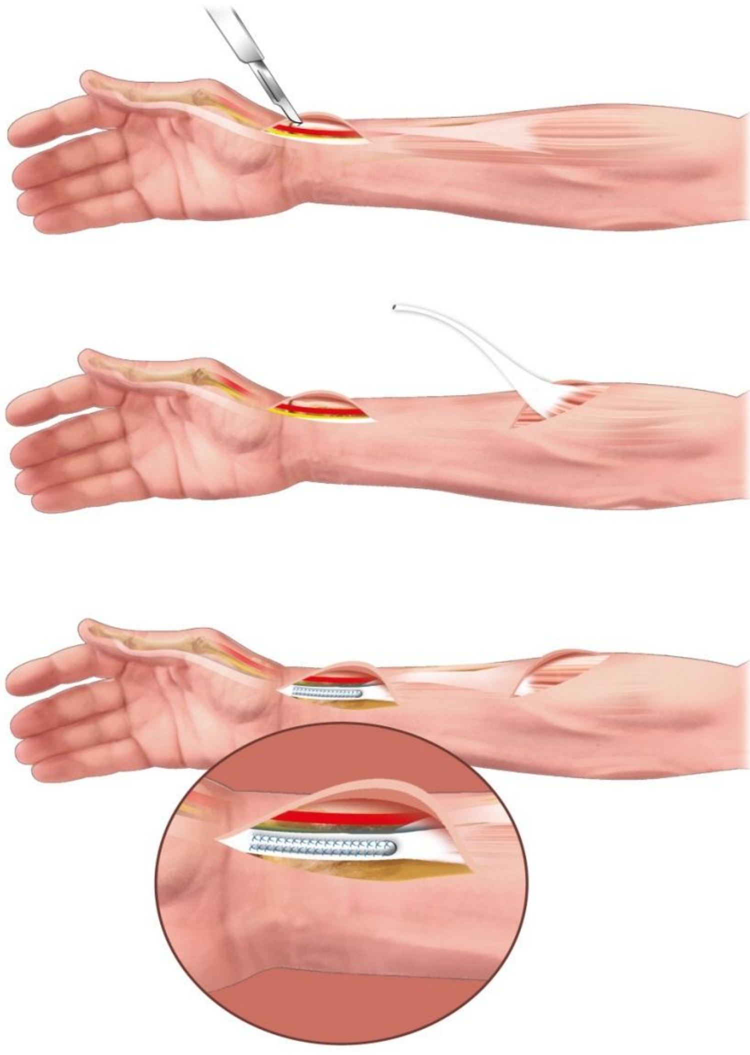


Figure 4. BR-FPL tendon transfer.

3.5.2 ECRL-FDP Tendon Transfer (Study II and IV)

The extensor carpi radialis longus (ECRL) is accessed through a transversal incision just proximal to its insertion on the basis of the 2nd metacarpal. An incision at the insertion site is made. To be on the safe side extensor carpi radialis brevis (ECRB) is identified before the ECRL tendon is detached. The tendons of flexor digitorum profundus (FDP) are identified and the ECRL tendon is passed obliquely through the tendons of the FDP index-ring finger. FDP V is left out of the transfer, but will be passively flexed due to the connection between the FDP muscles of the ring finger and the little finger (Fridén, 2005). The tension and the finger cascade are checked before definite suturing. A bandage roll (roughly 4 cm in diameter) placed in the palm facilitates the tensioning of the fingers. (Figure 5)

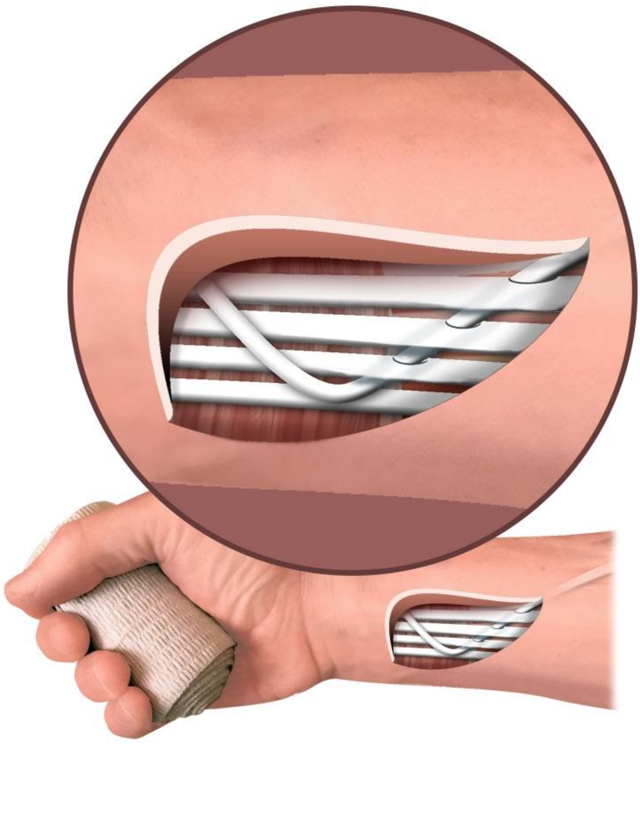


Figure 5. ECRL-FDP tendon transfer

3.5.3 Split FPL-EPL Tenodesis (Study II and IV)

Through a medio-lateral incision on the radial side of the thumb, the radial half of the FPL tendon is exposed and detached from its insertion. The tendon is then freed from the ulnar half and passed from the distal of the MCP joint subcutaneously and via an oblique route to the EPL dorsal of the interphalangeal (IP) joint. Through a dorsal incision the split FPL is sutured to the EPL. A test suture is recommended to set the right tension which allows 20-30º of flexion of the IP joint, when the FPL is pulled (Mohammed et al, 1992) (Figure 6).

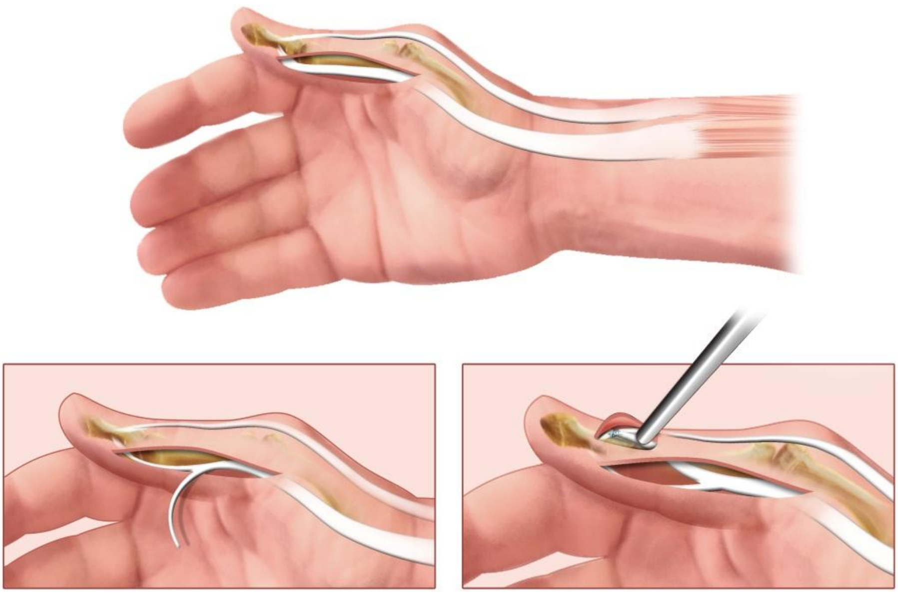


Figure 6. Split FPL-EPL tenodesis.

3.5.4 CMC I Joint Arthrodesis (Study II and IV)

A dorsoradial incision is made over the first carpometacarpal (CMC) joint. Attention is paid to the nerve branches of the radial nerve, and to the artery in Tabatiere´s fossa. The joint capsule is incised, and the articular cartilage is gouged out with a rongeur. A functional position of the thumb is to face slightly distal to the 2nd PIP joint that gives the best opportunity for a good key pinch. The arthrodesis is secured with a locking low-profile T-plate. Locking-plates are considered to provide more stable fixation and are associated with fewer non-unions than conservative fixation methods (Ruchelsman et al, 2010) (Figure 7).

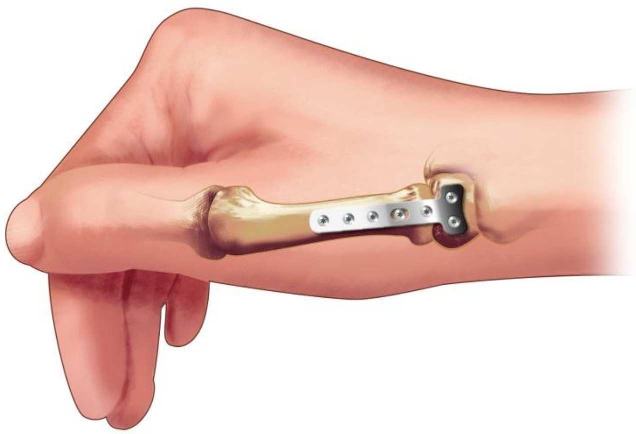


Figure 7. Arthrodesis of the first CMC joint. Note the positioning of the key pinch.

3.5.5 EPL-tenodesis (Study II and IV)

The extensor pollicis (EPL) tenodesis requires an arthrodesis of the first CMC joint to be effective. The EPL tendon is released from the tendon muscle junction, and then rerouted around the APL tendon for a true radial abduction of the thumb. Before securing the EPL tendon to the fascia between the 3rd and 4th extensor compartments the abduction need to be adjusted. At wrist flexion, the volar abduction should be at its greatest: and at wrist extension, the tension should allow for thumb flexion (Figure 8).

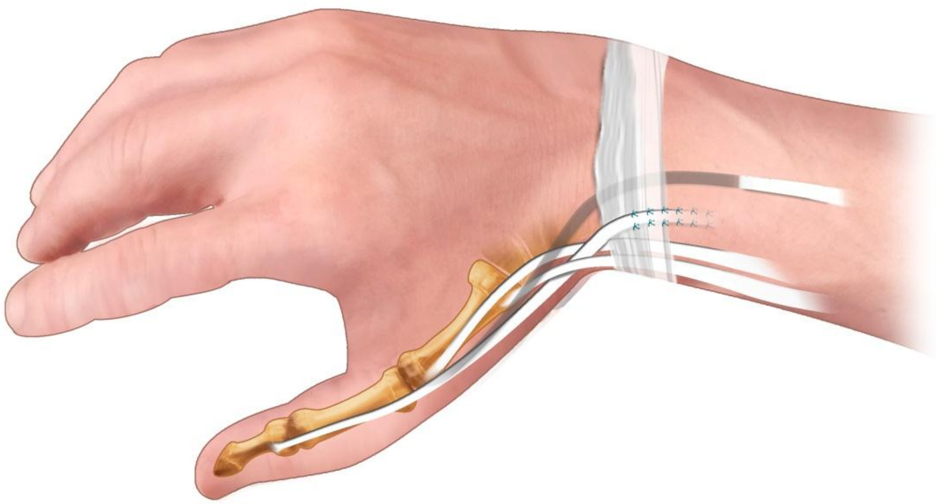


Figure 8. EPL-tenodesis. The EPL is detached (former route is grey) and rerouted.

3.5.6 ECU-tenodesis (Study II-IV)

ECU tenodesis is a passive tenodesis (Hentz and Leclercq, 2002). A curved incision is made over the ulnar head and the 6th extensor compartment is opened. The dorsal sensory branch of the ulnar nerve is protected. Using a tendon elevator while the assistant brings the wrist into ulnar deviation, the tendon is lifted and shortened until the radial deviation deformity is gone. The duplication is secured with 2-0 TiCron mattress sutures and the tendon loop is then secured onto the ulnar head (Figure 9).

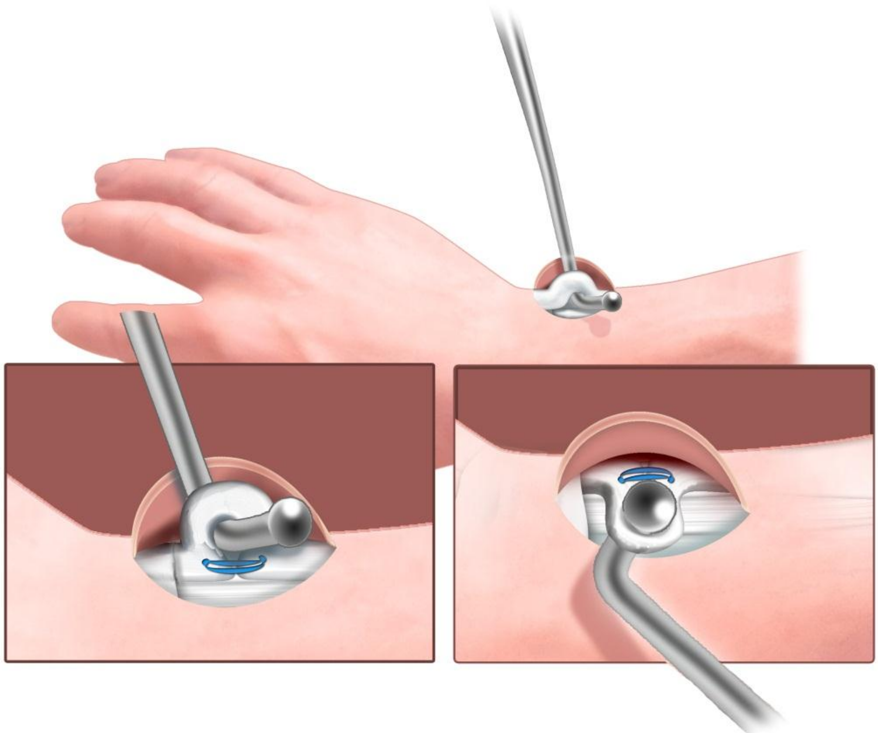


Figure 9. ECU-tenodesis.

3.5.7 House´s Tenodesis (Study II and IV)

To reconstruct the passive interossei according to House (McCarthy et al, 1997), the FDS of the 4th finger is harvested from its insertion and longitudinally divided through its junction. The tendon is cut at the muscle level and divided into 2 slips. Oblique incisions are made on the dorsal aspect of the proximal phalanx of each finger. Transversal incisions are made on the dorsum of the hand at the level of the 2nd and 4th metacarpal necks. With the MCP joints in 60º of flexion, the first FDS slip is tunneled from the radial side of the proximal phalanx of the index finger under the insertion of the first dorsal interosseus muscle, and then under the extensor digitorum communis of the index (EDC) II and extensor indicis proprius (EIP) tendons. Then the tendon slip is tunneled through the lumbrical canal, volar to the intermetacarpal ligaments, and sutured onto the lateral and central band of the middle finger while the PIP joints are extended and the MCP joints are flexed at 60º. The other tendon slip is used for the ring and little finger with the same procedure. The PIP extension should be protected during the operation with a roll of elastic bandage placed in the palm (Figure 10).

Figure 10. House´s tenodesis.

3.5.8 Distal Ulnar Intrinsic Release (Study I and V)

The extensor mechanism is exposed through a dorsal oblique incision on the proximal phalanx. The ulnar side of the aponeurosis is identified and a triangular piece containing the lateral band and the oblique fibers is resected. The release is sufficient when the intrinsic tightness, as described by Bunnell´s intrinsic tightness test, is gone (Figure 11).

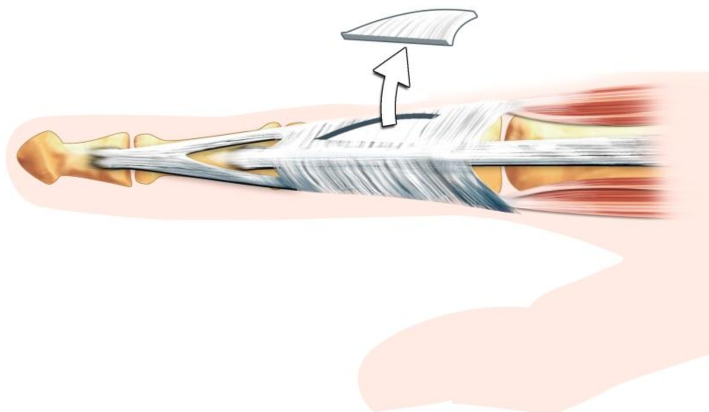


Figure 11. Distal ulnar intrinsic release.

3.5.9 The Zancolli-Lasso Procedure (Study IV)

The Zancolli-Lasso procedure is a functional dynamic tenodesis, in which each FDS is looped around its corresponding A1 pulley, which was designed to correct claw deformity and intrinsic minus position (Zancolli, 1957).The goal of the Zancolli-Lasso procedure is to provide flexion at the MCP joints and thereby allow the EDC to extend the IP joints.

3.5.10 Tendon Lengthening (Study I and V)

The tendons of the finger and wrist flexors are long. From a curved incision on the distal volar part of the forearm, 7-8 cm of the tendons can be exposed. A long step-cut incision (Z-incision) in the tendon is made. Lengthening of 2-3 cm is usually required, which also allows for side-to-side sutures with a 4-5 cm overlap. The lengthening should put the tendon-muscle unit in a “normal” resting position. Attention should be paid to the finger cascade (Figure 12).

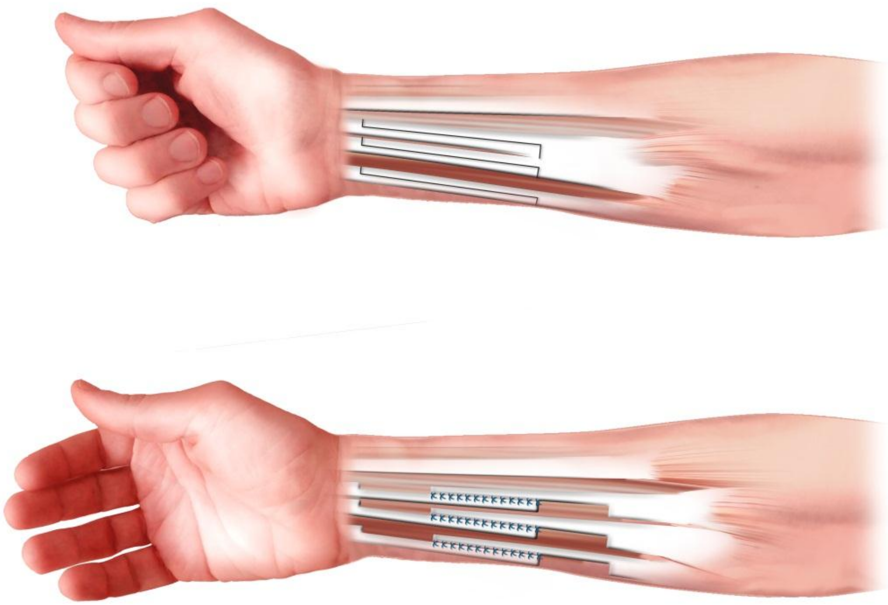


Figure 12. Tendon lengthening.

3.5.11 Release of AdP (Study I and V)

A small dorsoulnar incision is made at the first MCP joint. The insertion of the adductor pollicis (AdP) is identified and released (Figure 13).

Figure 13. Release of AdP.

3.5.12 Release of PT (Study I and V)

The pronator teres muscle (PT) inserts on the midst of the radius radially. Through an angled incision, the short tendon can be released (Figure 14).

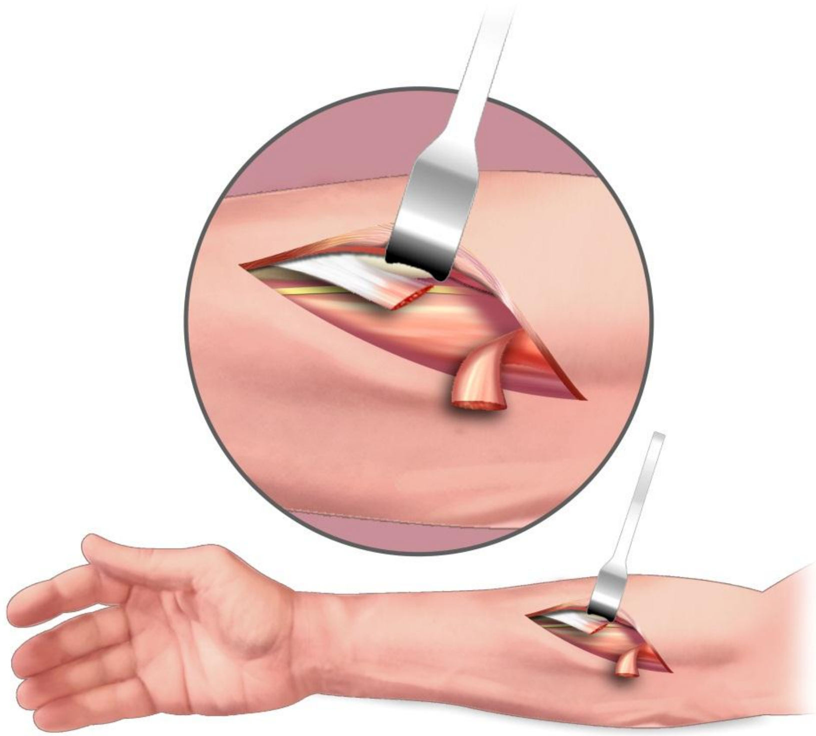


Figure 14. Release of PT.

3.5.13 Side-to-side Sutures (Study I-V)

Side-to-side sutures are used in tendon transfers and tendon lengthening. The tendons are sutured side-to-side with cross-stitches running along both sides, overlapping 5 cm of donor and recipient tendons. In vitro studies have shown that failure to load is more than 20 kg on this attachment (Brown et al, 2010), which is twice as strong as the Pulvertaft weave, recently used for all tendon attachments (Figure 15).

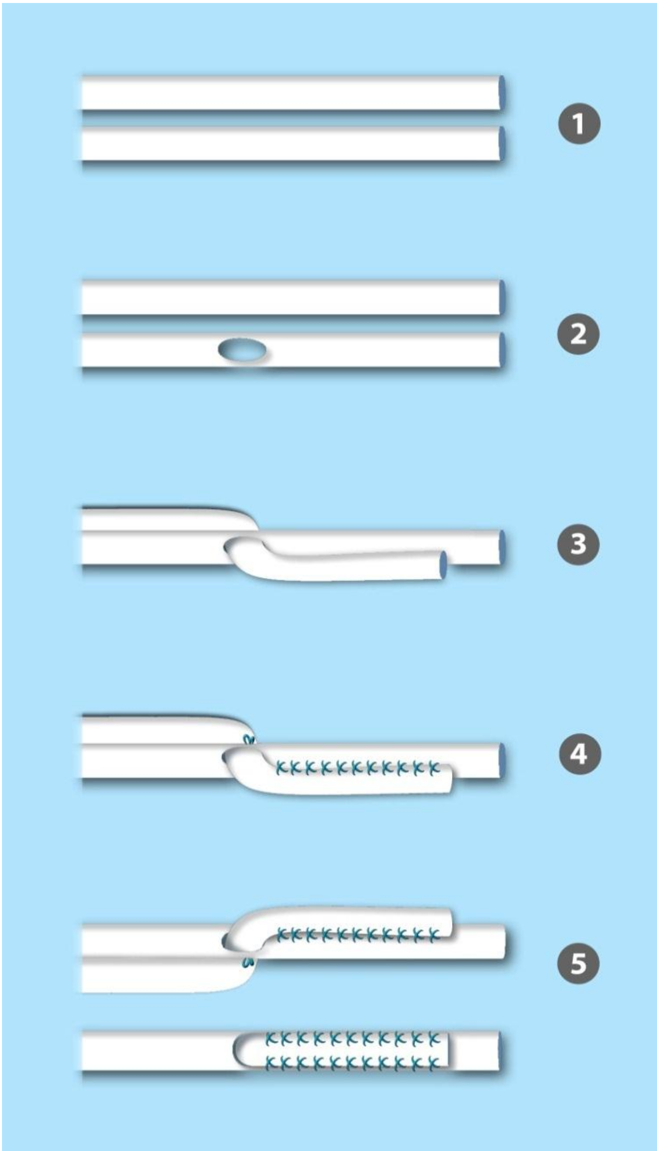


Figure 15. Side-to-side sutures step by step.

3.5.14 The Alphabet Procedure (Study II and IV)

The alphabet procedure is a combination of surgical procedures, customized according to the patient´s needs. A typical OCu 4 patient will undergo: split FPL-EPL tenodesis, reconstruction of the interossei, CMC joint arthrodesis, BR-FPL transfer, ECRL-FDP transfer, EPL tenodesis and ECU tenodesis.

3.6 Postoperative Treatment/ Rehabilitation

All patients, both in study groups and control groups, had early active training that started on the first postoperative day. All patients who were immobilized with casts were excluded from the studies. During the first 4 weeks, patients performed functional training to allow for movement of the tendons transfers, tenodeses or tendon lengthening. This is important to avoid edema and adhesions. In patients who received the alphabet reconstructions, full flexion of the fingers was restricted during the first 4 weeks to protect their reconstructed interossei. Resting splints were used between training sessions. Patients were discharged from the hospital 3 days after surgery, equipped with a self-directed training protocol to follow. After 4 weeks, the patients returned to the hand surgery ward for task-oriented training which lasted for 4-8 weeks. Splints and restrictions on loading and activity were removed 12 weeks postoperatively.

3.7 Spasticity-reducing Surgery

Patients with spasticity in study I and V underwent tendon lengthening, release of the AdP, PT and distal ulnar intrinsics customized to their symptomatology (Table 4).

Table 4. Algorithm for spasticity-reducing surgery.

Spasticity	**Affected muscle**	**Surgical procedure**	**Function**
Fingers	FDS	Tendon lengthening	Opening of the hand
Fingers	FDP	Tendon lengthening	Opening of the hand
Fingers	IO	Release of interossei	Reduction of intrinsic tightness, better grip
Wrist	FCR	Tendon lengthening	Wrist extension possible
Thumb	FPL	Tendon lengthening	Thumb extension possible
Thumb	AdP	Release of the AdP	Better opening of first web space
Pronation deformity	PT	Release of the PT	Supination possible

3.8 Statistical Analysis

For comparison of differences in mean ROM values, one-way ANOVA was used with severity serving as the repeated factor (study I). One-way ANOVA was also used for comparison of strength values between the study and control group (study III), as well as for comparison of joint angular velocity and repetitions per second pre-and postoperatively (study V). The Mann-Whitney test was used to differentiate between the individual fingers within the groups (study I). Paired students' t-tests were used for comparison of pre- and postoperative changes of radial deviation in the ECU-tenodesis group (study III), and between the means of COPM (study V), and between postoperative clinical data in the study and comparative groups (study IV). The grip strength data in the comparative group (IV) did not have Gaussian distribution. Additional Mann-Whitney tests confirmed significant differences of means and medians between the groups. Unpaired t-test data are shown (study IV). Significance level (α) was set to 0.05 for all statistical tests.

4 RESULTS

The patients improved overall the measured parameters. Grip strength was doubled (study III and IV), and opening of the first web space (IV) and ROM (I) were improved. Voluntary grasp and release movements measured as repetitions per second were significantly better after spasticity-reducing surgery in study V. Patient satisfaction and performance (COPM) were overall improved more than 2 points indicating clinical relevance. Table 5 demonstrates an overview of the significant results.

4.1 Study I

Patients with intrinsic tightness, in the mild group had an immediate effect of the distal ulnar intrinsic release at 1 month postoperatively and they kept this good result. Significant results were found in the long finger, where the increase went from 65º to 90º, which was an improvement of 38%. In the severe group, the patients needed up to 6 months before showing improvements of their ROM. Significant increases in ROM were in the long and ring fingers, 35% and 45%, respectively. Figure 16 and 17 show the mean passive ROM (PIP joints) of all the operated fingers in each group.

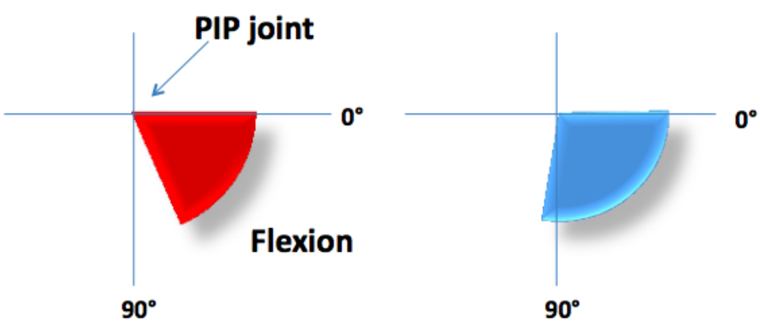


Figure 16. Mild group (study I). Passive ROM of the PIP joints before (red) and 6 months after (blue) distal ulnar intrinsic release.

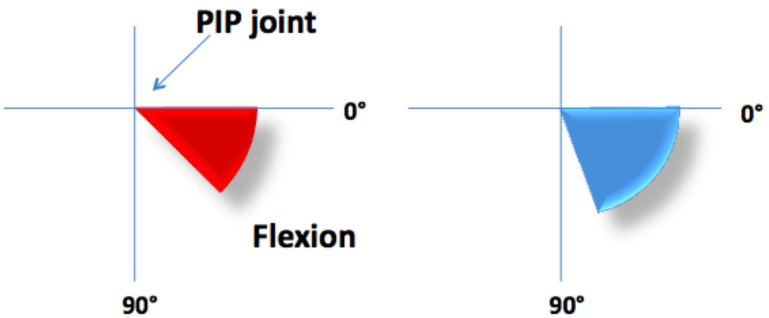


Figure 17. Severe group (study I). Passive ROM of the PIP joints before (red) and 6 months after (blue) distal ulnar intrinsic release

4.2 Study II

25 cases underwent the alphabet procedure (single-stage grip reconstruction) and achieved active finger flexion, active thumb flexion, and passive extension of fingers and thumb; grip and release function. A single-stage operation is proven possible and saves the patient from two-stage reconstructions (flexor and extensor phase) with two rehabilitation periods per limb. Key pinch and grip strength were measured at the three different clinics. Key pinch ranged from 10-40 N and grip strength 20-80 N.

Table 5. Overview of significant results.

Study **(Surgical procedure)**	**Groups**	**Significant results** **(±SEM)**
Study I (Distal ulnar intrinsic release)	Mild intrinsic tightness (n=14)	Increase of ROM (PIP III) 25° (p<0.05)
	Severe intrinsic tightness (n=23)	Increase of ROM (PIP III) 35° (p<0.05), ROM (PIP IV) 45° (p<0.05)
Study III (ECU-tenodesis)	Study group (n=18)	Correction from 23±1.5°preop to 3±1.8° postop (p<0.001)
	Study group vs. control group (n=43)	Grip strength (study) 6.1±1.2 kg vs. (control) 2.8±0.6 kg (p<0.01)
Study IV (The alphabet procedure)	Study group (n=16) vs. Comparative group (n=18)	Grip strength (study) 6.53±0.69 kg vs. (comparative) 1.58±0.69 kg (p<0.001) Opening of the first web (study) 5.47±0.65 cm vs. (comparative) 2.97±0.46 cm (p<0.01)
Study V (Spasticity assessment)	Study group (n=8)	Joint angular velocity at 20s 23.2±4.0°/s preop vs. 48.7±11.4°/s postop (p<0.01) Repetitions 0.35±0.02 rep/s preop vs. 0.45±0.03 rep/s postop (p<0.001) COPM (sat) 3.4±0.76 points COPM (per) 2.8±0.72 points (p<0.01)

4.3 Study III

The patients in the study group with ECU-tenodesis had 23º of radial deviation of the wrist joint preoperatively and 3º of radial deviation postoperatively at 6 months. The correction was significantly improved. Grip strength was postoperatively more than double and significant in the study group, 6.1 kg compared to 2.8 kg in the control group without ECU-tenodesis. Pinch strength and opening of the 1st web space were not significantly different between the groups (Figure 18).

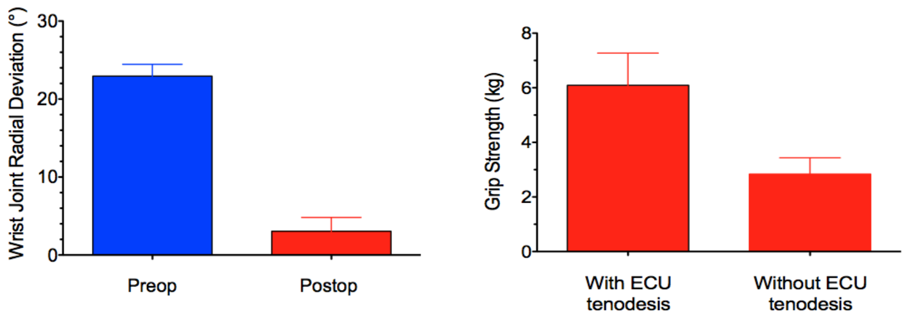


Figure 18. Study III The figure to the left shows the degrees of wrist radial deviation before (blue) and 1 year after (red) surgery. The figure to the right compares the grip strength between the study group with ECU-tenodesis and the control group without ECU-tenodesis 1 year postoperatively.

4.4 Study IV

The postoperative grip strength of the study group with the alphabet procedure was 6.5 kg compared to 1.6 kg in the historical comparative group (p<0.001). Pinch strength was not significantly different between the groups, 2.8 kg in the study group compared with 2.0 kg. Opening of the first web space was significantly larger in the study group; 5.5 cm compared with 3.0 cm (p<0.01) (Figure 19). COPM demonstrated clinical improvement of the study group patients, by differences larger than 3 points (Figure 20).

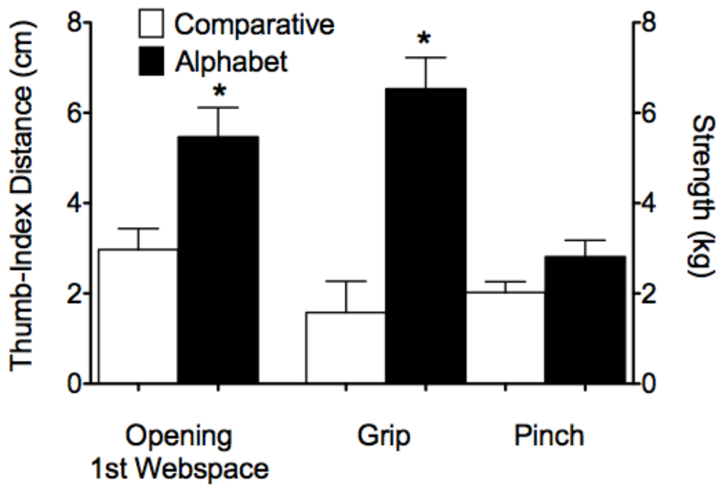


*Figure 19. Study IV: The study group (alphabet procedure) and comparative group (traditional grip reconstruction) with assessed parameters: opening of the 1st web space, grip strength and pinch strength. * = significant results.*

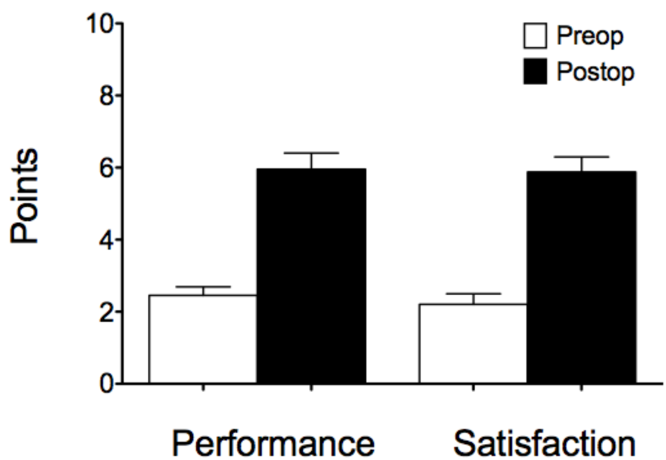


Figure 20. Study IV: The outcomes of COPM. A difference of more than 2 points is considered clinically relevant.

4.5 Study V

Electro-goniometry DataLINK by Biometrics (Newport, UK) is a feasible instrument in clinic to evaluate the outcomes of spasticity-reducing surgery. Joint angular velocity was calculated and repetitions per second were easily demonstrated. This method is applicable in a clinical setting. Together with COPM, these three points of assessment give valuable data for evaluation of spasticity-reducing surgery. Reliability and validity are high. Joint angular velocity was only significant at 20 seconds for the wrist joint (Figure 21), 23°/s preoperatively increased to 49°/s postoperatively ($p<0.01$). Repetitions per second were 0.35 rep/s preoperatively and 0.45 rep/s postoperatively (0.5 rep/s is maximum at this metronome rate) ($p<0.001$) (Figure 22) COPM points were significantly improved both in satisfaction and in performance.

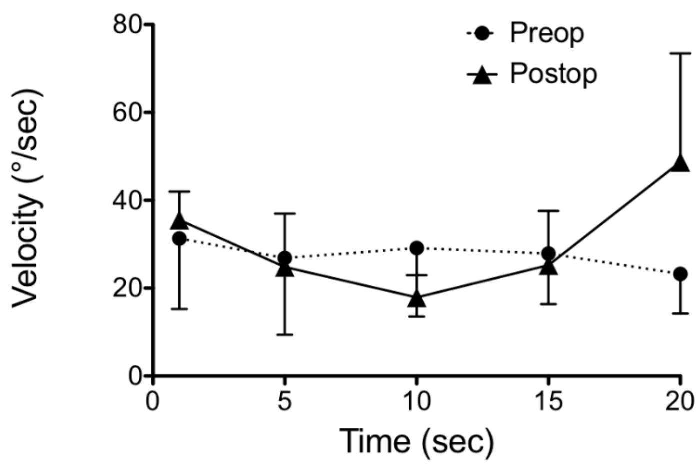


Figure 21. Study V: Joint angular velocity of the wrist joint measured during 20 seconds of flexion and extension, before and 6 months after surgery. At 20 seconds the joint angular velocity was higher than before surgery indicating that spasticity is reduced and voluntary movements are easier.

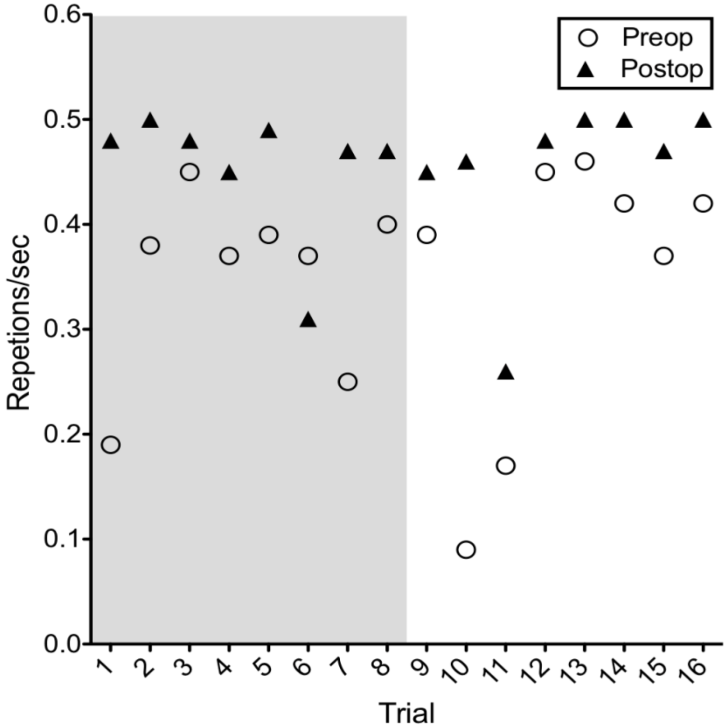


Figure 22. Study V. Test results of repetitions per second shown on individual basis (2 test results per patient and joint preop and postop for PIP III and wrist joints respectively). One repetition consists of full flexion= 1 s and full extension= 1 s, and accordingly 0.5 repetition can maximally be performed per second. Shaded area to the left represents PIP III and white background to the right depicts the wrist joint.

4.6 Complications

One patient had a postoperative hematoma, which eventuated in tenolysis (study II, IV). One patient had a non-union of the arthrodesis of the first CMC joint (study II, III, IV). Reoperation was performed using a locking-plate, which was successful. 4 patients had problems with progressive spasticity (study III). One patient had a superficial wound from splint pressure, which healed with conservative treatment (study IV). One House´s tenodesis did not hold and had to be revised (study IV). 4 patients could not make a full fist, and the remaining digit-to-palm gaps were 1 cm (3 patients) and 2 cm (1 patient) (study IV). One patient had a self-inflicted wound, which resulted in extensive adhesion formation, which had to be surgically released (study IV).One patient was not happy with the opening of the hand and had the possibility to get active extension of the fingers, as in the traditional regimen (study IV).

5 DISCUSSION

One important reason why more surgical procedures can now be performed simultaneously is the development and implementation of an improved tendon-to-tendon attachment in tendon transfer surgery. Side-to-side sutures are twice as strong as traditional Pulvertaft attachments (Brown et al, 2010). This fact has allowed for a more aggressive and active postoperative training (Fridén & Reinholdt, 2008). Another important study has demonstrated a safety factor between 5 and 10 for BR-FPL tendon-to-tendon attachment at ultimate load (Fridén et al, 2010). Consequently, this has strongly contributed to the development of grip reconstructions such as the alphabet procedure. Knowing that tendon-to-tendon attachments are stronger also allows for more spasticity-reducing surgery. Multiple tendon lengthening requires early active training to gain better ROM and better control.

Combining multiple surgical procedures simultaneously is not only more convenient for the patient, but also cost-efficient. The complication rate is low and the patient safety is maintained. Cutting down on one operation and one rehabilitation period means 10 days less hospital care and fewer visits to the outpatient clinic. Considering that this counts per limb, the sum that is saved per patient is huge. The number of procedures in tetraplegic patients has increased (Figure 2), but the number of patients is almost the same. More reconstructive procedures allows for more functions. Another economical aspect is the higher degree of autonomy and hand function the patients achieve by surgical restoration. Being able to do more by themselves mean less need of personal assistance. Some patients have gone back to a part-time job due to better hand function. The socioeconomic profits are probably enormous.

5.1 The Alphabet Procedure (Study II & IV)

In study II patients were collected from three units that perform the alphabet procedure. The design of this study was to describe the surgical technique and demonstrate that a single-stage operation works to reconstruct pinch, grasp and release function. Key pinch and grip strength were collected at different sites by different examiners. Study IV concentrates on the actual outcomes of the alphabet procedure and to minimize confounding factors by stratifying the population to only include OCu 4 patients.

In study IV classification group OCu 4 constitutes a stratified sample from the population of patients who underwent grip reconstructions. OCu 4 is the largest and most common group. The alphabet procedure is, however, performed in other classification groups, but these groups are smaller and therefore not suitable for any statistical analysis. When the alphabet procedure is performed in other classification groups, the kit of procedures is customized depending on classification level and individual needs. This is a consequence of variability between patients, both in the classification group as well as in injury presentation. 27 individuals, O 3-OCu 8, underwent the alphabet procedure and were followed up with 1 year postoperatively. All patients with the alphabet reconstruction classified as OCu 3-5 had tendon transfers of BR to FPL, and ECRL to FDP, and House´s tenodeses. Most patients also underwent arthrodesis of the 1st CMC joint and a split tenodesis of FPL to EPL. In higher classification groups (OCu 6-8), there was less need for arthrodeses and split FPL-tenodeses. Instead, four patients received transfers of EDM to APB (Fridén et al, 2012). Each classification group gets its own surgical profile (Figure 24). Active reconstruction of the interossei is an option for patients who have a functional flexor digitorum superficialis (FDS) muscle and provides a good alternative to the passive reconstruction achieved by House's tenodesis. Five patients of OCu 6-8 underwent this procedure.

Most patients in classification groups OCu 3-5 required all the 7 procedures of the alphabet procedure, but patients in higher classification groups may not need all seven procedures. Generally speaking, higher classification levels allow for more customization. The planning of surgical procedures is clarified in an algorithm (Figure 23). In addition to classification group differences, injury presentation can differ between patients of the same group, which can also necessitate procedure customization. For example, some patients had a good natural tenodesis of the thumb and did not need an EPL-tenodesis. In addition, some patients did not exhibit an obvious radial deformity of the wrist, so they did not require ECU-tenodesis.

During collection of patients from the registry in study IV there were 27 patients (37 hands) found with traditional grip reconstruction and early mobilization. Grip reconstruction in the traditional group was also customized according to the classification level. Patients with lower classification levels generally had an arthrodesis of the first CMC joint and a split thumb tenodesis while patients with higher classifications needed these operations less frequently. Several patients in the traditional group had Zancolli-Lasso procedures (Zancolli, 1957) (Figure 25). All patients in the traditional groups underwent the flexor phase of grip reconstruction, but surprisingly only one chose to continue with the extensor phase. It is reasonable to interpret this behavioral pattern as an unwillingness to undergo

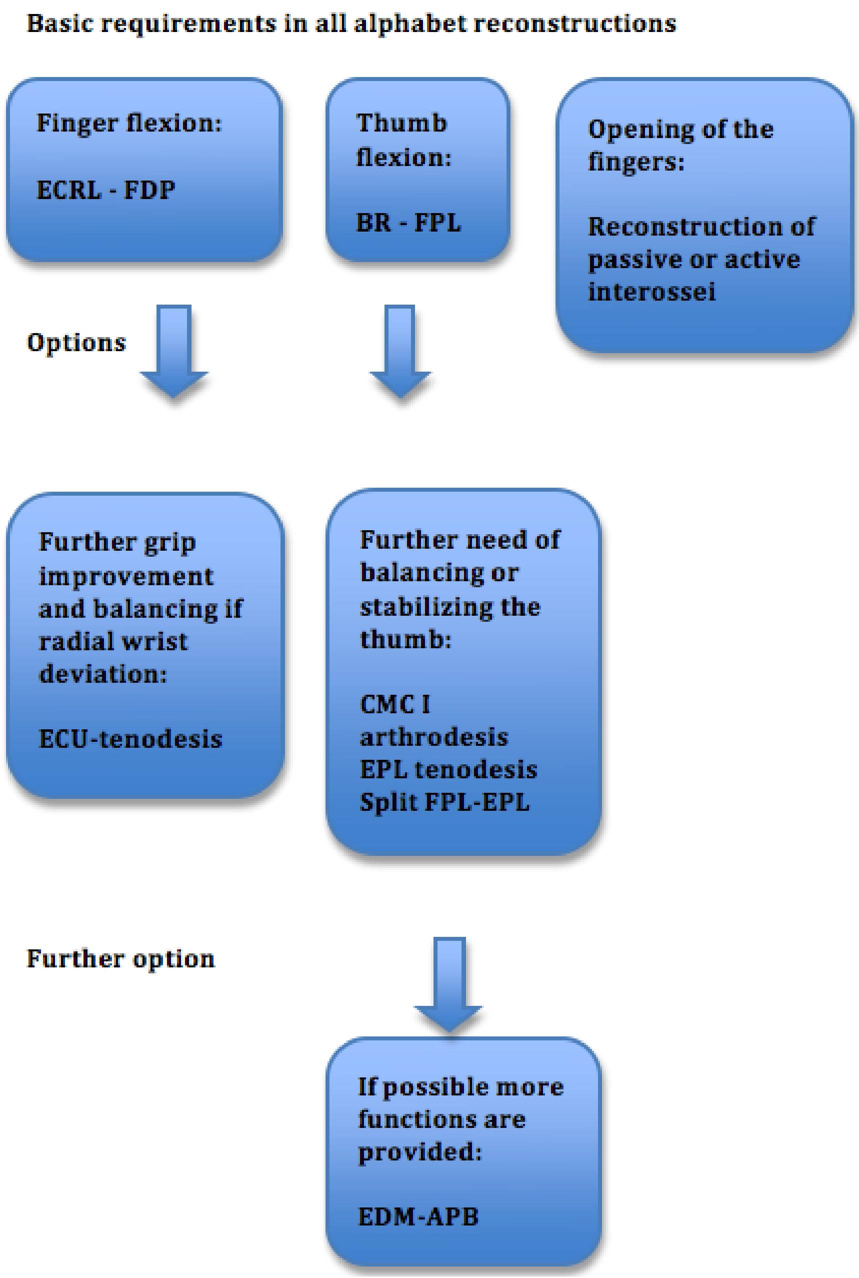


Figure 23. Algorithm of surgical planning of the alphabet procedure

yet another operation on the same hand to achieve only somewhat better function. Instead, patients appear to prefer investing necessary rehabilitation time and effort into reconstruction of contralateral hand function. This interpretation further strengthens the idea that patients favor a single-stage full reconstruction of hand function. It allows for a more expedient turn-around of hand surgery service in this population of patients, which has an extensive need for improved hand control.

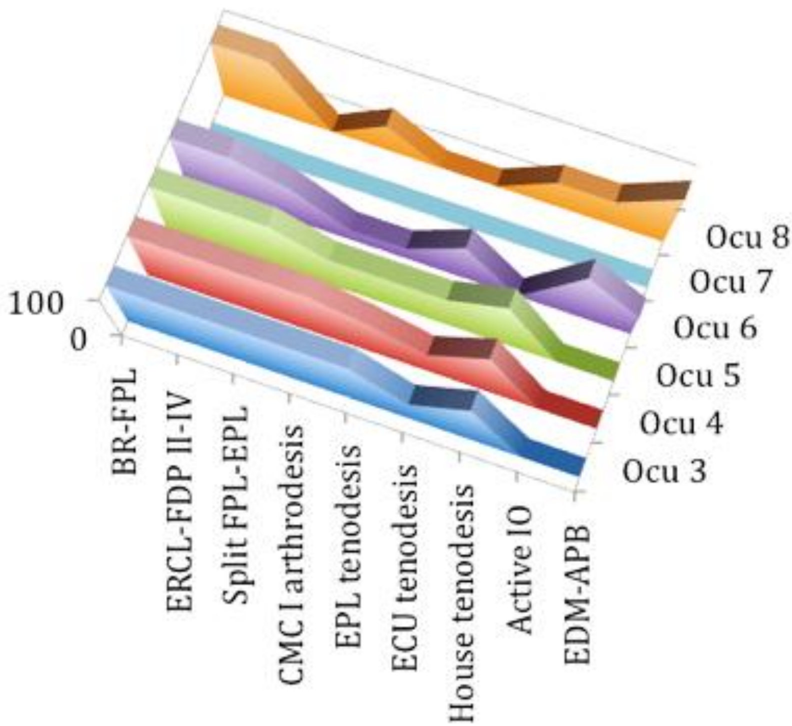


Figure 24. Surgical profile of alphabet reconstructions, demonstrating the types and amounts of procedures received. The height of the bar represents the percentage of patients within a specific functional group that received a given procedure. Note that the higher classification groups have less need of stabilizing procedures.

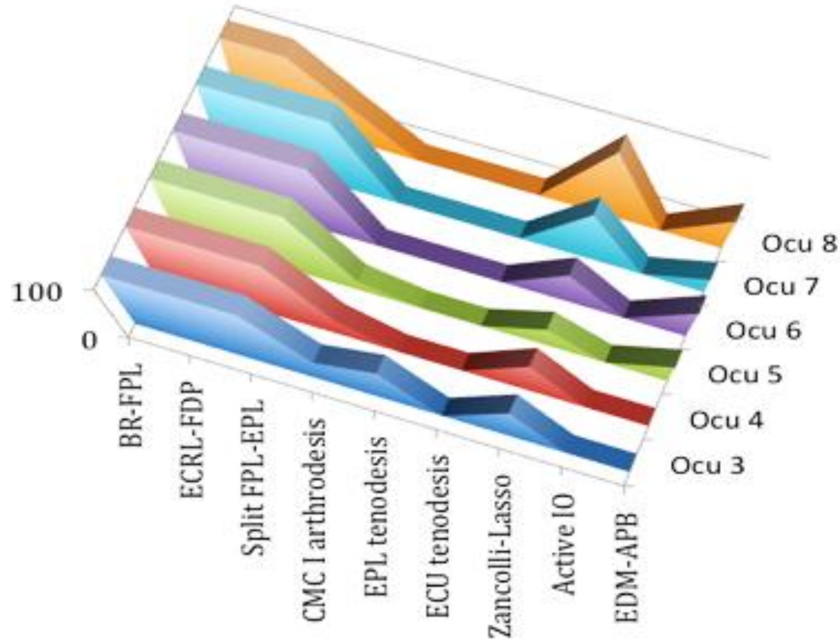


Figure 25. Surgical profile of the traditional grip reconstruction group. Graph orientation and axes are similar to Figure 24.

Patients in the traditional group frequently underwent the Zancolli-Lasso procedure, a functional dynamic tenodesis in which each FDS is looped around its corresponding A1 pulley, which was designed to correct claw deformity and the intrinsic minus position (Zancolli, 1957). The intrinsic minus position is characterized by hyperextension of the MCP joints and extension loss at the IP joints. The goal of the Zancolli-Lasso procedure is to provide flexion at the MCP joints, and thereby allow the EDC to extend the IP joints. However most tetraplegic patients lack proper EDC function and therefore cannot achieve IP joint extension. Thus, while the Zancolli-Lasso procedure reduces the intrinsic minus position by producing flexion of the MCP joints, its lack of action at the IP joints is a major shortcoming. House´s procedure, in which donor tendon slips are sutured onto the extensor mechanism’s central slip and lateral bands, provides passive IP joint extension and MCP joint flexion: thereby providing a better opening grip configuration for the tetraplegic patient. The House procedure is also faster to perform, while the Zancolli Lasso procedure is trickier to perform since the suturing is in the palm with flexed fingers. It is important to underline that the purpose of House´s procedure is not to correct clawing, which none of the patients in the study group had, but to reconstruct extension of the PIP joints for better opening of the hand.

The IP joint extension/ function of the interossei can also be made active by using an active FDS IV tendon and splitting it into 4 slips, if the tendon size allows it. If not; FDS III and FDS IV are split into 2 slips each instead. This Stiles-Bunnell transfer (Bunnell, 1942) can be considered in cases with incomplete tetraplegia or in patients with a high classification e.g. OCu 8.

In study IV, the results of grip strength of the comparative historical group were scattered and did not show a Gaussian distribution. This may indicate low precision at measuring with the Jamar device. Some patients were quite strong and several patients had very weak or not even measurable grip strength. In the national register, several examiners did the measurements. It is therefore, difficult to know whether the patient really tested the active flexor function of the fingers or if the patient was allowed to use the tenodesis effect at measurement. Some patients may have very little or no active function, but a strong tenodesis grip powered by wrist extension.

The average number of simultaneous procedures was 7 in the alphabet procedure groups and 3-5 in the traditional groups. Because they received more simultaneous procedures, patients in the study group needed more tendon balancing and more tenodeses to “normalize” the hand’s appearance (and possibly also function). One consequence of this increased number of simultaneous procedures is a greater risk of swelling, which is best mitigated through an ambitious postoperative training program that requires a willing and highly motivated patient. Rehabilitation protocols for both groups included early active mobilization, but the study group received more mobilization and had fewer activity restrictions. The rationale supporting the more ambitious protocol of the study group includes evidence that the side-to-side suture method is strong enough to allow early active mobilization (Brown et al, 2010) and can provide excellent safety margins (Fridén et al, 2010) in tendon transfers. Fewer restrictions and greater mobility helped reduce the substantial swelling and adhesion formation that would otherwise occur as a result of the many simultaneous procedures. I presume that the new and less restrictive regimen is also more appealing and less frustrating for the patient

Over the past few years we have gradually transitioned from using K-wires and staples to using locking low-profile T-plates (Compact Hand 2.0 Synthes, Solothurn, Switzerland) for the CMC joint arthrodesis. Since this change we have not had any patients return postoperatively with non-union or delayed union of the arthrodesis. In the study there was only one patient with a non-union, which had K-wires and staples. At reoperation, a locking-plate was used with successful healing. Since many tetraplegic patients have low quality or osteoporotic bone, a locking plate seems to be a safer option.

Triceps reconstruction is important for the hand function, and should preferably be performed prior to grip reconstruction (Fridén, 2005). Stability of the forearm and hand is critical for the grip control. Among the study patients, all except one had undergone triceps reconstruction (posterior deltoid to triceps (Fridén et al, 2000)) or had functional triceps.

Grip strength and opening of the first web space were significantly larger in the study group compared with the historical group. One possible explanation to the large difference in grip strength may be the added ECU-tenodesis, as demonstrated in study III. A good opening of the hand depends on a stable thumb (arthrodesis of the first CMC joint) and EPL-tenodesis (House et al, 1992), which improves the web spread, as well as the House´s tenodesis. Reconstruction of the interossei definitely has an effect on grip strength. How much passive interossei, as in the study group, affect the grip strength is unclear. The presence of antigravity wrist flexion benefits the opening of the hand. Activity in the flexor carpi radialis (FCR), even muscle strength grade 1-3, may improve the hand opening. Function of the FCR increases the natural extension tenodesis effect at wrist flexion. Some patients in study IV had low grade strength of the FCR, yet not grade 4, as that would mean

ICSHT group OCu 5 instead of OCu 4. Better opening of the hand may increase the use of the reconstructed hand and consequently lead to improved grip strength.

5.2 Distal Ulnar Intrinsic Release (Study I)

Spastic or tight interossei are found in patients with incomplete tetraplegia and spasticity. It can be solitary or hidden behind spasticity of the FDS and FDP muscles. Naidu and Heppenstall (1994) distinguished two groups depending on the involvement of the MCP joints: a mild and a severe group. In the clinic the patients with affected MCP joints had clenched fists with spasticity in all extrinsic flexors and interossei. The mild group with no involvement of the MCP joints had focal spasticity with spasticity in the interossei and partial spasticity in the extrinsics. The mild group reached almost full ROM within the first postoperative month and kept up the good results. The severe group, with often general spasticity, needed a longer time for rehabilitation and did not reach results as good as the mild group. The results of the severe group were however improved by 45 %.

Bunnell's test for intrinsic tightness is not tested for validity and repeatability. It has however been used by hand surgeons for decades and is well-known. Since it tests the intrinsic tightness passively it can be used peroperatively to reassure the surgeon that the distal ulnar intrinsic release is sufficient.

5.3 ECU-tenodesis (Study III)

Besides from improving the grip strength, balancing the wrist may be of prophylactic ergonomic value. With a straight wrist the patient does not have to rotate externally with the shoulder to grasp objects. Many patients with tetraplegia suffer from shoulder pain, 59% in a study by Curtis et al (1999).

5.4 Spasticity Assessment (Study V)

In study V, some patients were satisfied and performed better even though their joint angular velocity had not necessarily improved. The patients achieved more repetitions per second and could maintain the movements for a longer amount of time. Keeping the metronome pace means improved control, which was reported by the patients in their COPM interviews. The patient who showed the worst results stated that her grip was better and that her shoulder was better due to less tension. See figure 26 for summarized results from study V. Using the three assessment points; joint angular velocity, repetitions per second and COPM give a wider picture of the outcome of spasticity-reducing surgery.

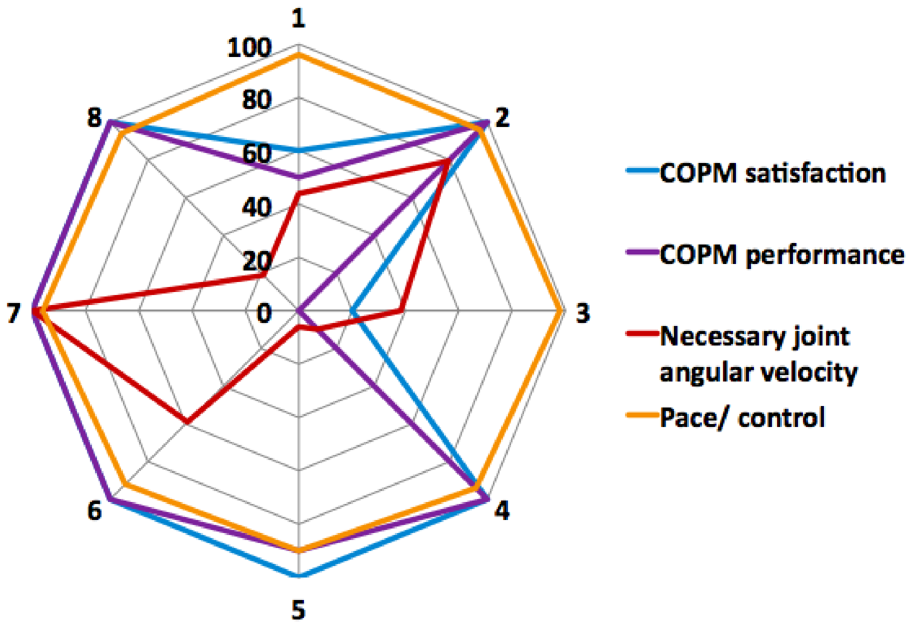


Figure 26. Figure 26. Summarized results from study V. Each vertex of the octagon represents a patient in the study. The scale is in percentage. 2 COPM points= 100%, 0.5 repetition= 100%, 100 °/s = 100% in joint angular velocity, which is necessary for full ROM in the set pace. Some patients did not achieve a great joint angular velocity, but were satisfied anyway, probably due to better control.

COPM, which is nowadays a standard assessment at our clinic, adds qualitative data to the other quantitative data (grip strength, ROM, key pinch etc.) we produce. Patients´ experiences of the surgical outcomes are individual, such as the goals for the operation. The combination of COPM results and the quantitative data provide us with a broader view of the surgical outcomes. COPM is more useful and specific for patients with tetraplegia compared to the DASH questionnaire. COPM was recommended for tetraplegia research by consensus at the 8th Tetraplegia meeting in 2004 (Bryden et al, 2005).

In study V both finger and wrist flexors and extensors were tested in one movement, which may be too much to ask for at the same time. The reason for this set-up was to decrease the risk of muscle fatigue, but instead there is a risk for less performed ROM by the patient. Full flexion of the fingers is difficult at full flexion of the wrist. This does not influence the test of the method, but would affect the evaluation of the outcomes of spasticity-reducing surgery. Study V was, however, not designed to evaluate the outcomes of surgery.

After rehabilitation of spasticity-reducing surgery, patients often get better function of both the grip and release function. Sometimes is a function of antagonists (extensors) obtained. Preoperatively it is difficult to determine how much function there will be, and therefore, it is recommended not to combine spasticity-reducing surgery with reconstruction.

5.5 Updated Surgical Strategy by Classification Groups

The surgical procedures in studies I-V are already implemented in our unit. Treatment of patients with tetraplegia is often organized by ICSHT classification groups. Adding the latest contributions to science, the surgical strategy has been updated in Table 6.

5.5.1 O/OCu 0

Patients in group 0 have by definition no muscle groups below their elbow with grade 4 strength (Table 3). These patients may benefit from elbow extension transfer. Until lately surgical procedures for grip reconstruction have not been available for this group of patients. Dr. Fridén and Dr. Gohritz recently presented a new procedure: nerve transfer to reconstruct wrist extension (2012). A motor nerve branch is transferred from the brachialis to the ECRL. When active wrist extension is regained a passive key grip can be added.

5.5.2 O/OCu 1

Patients in group 1 have supination and elbow flexion and at least grade 4 strength of BR. The biceps and brachialis also provide elbow flexion, while the BR is available for transfer. The BR can be transferred to the ECRL and ECRB to provide wrist extension, which will work as a motor for a passive grip. For release of the pinch, EPL tenodesis is usually added. Further stabilization for the thumb is achieved by arthrodesis of the first CMC joint and split tenodesis of the FPL to EPL.

5.5.3 O/OCu 2-3

Patients in groups 2-3 have by definition a functional BR and wrist extensors. It is extremely difficult to determine the separate strength of the ECRL and ECRB. Therefore, it is hard to differentiate group 2 from 3. If both ECRL and ECRB are of grade 4 or more, a groove occurs between the muscles: Bean´s sign (Mohammed et al, 1992). If the PT is functional one can assume both wrist extensors are functional (Allieu, 1988). Moberg (1990) claimed that the only way to differentiate was by surgical exploration. Hentz and Leclercq (2002) recommend using the ECRL tendon only if ECRB is a grade 5 muscle. The BR is, however, available for transfer and can be used to power an active thumb or active fingers combined with a passive key grip, which is recommended to gain most functions. If the patient lacks pronation the BR can be routed dorsally and through the interosseus membrane to be attached with the FPL, to provide a dual function: active thumb flexion and pronation (Fridén, Reinholdt et al, 2012).

5.5.4 O/OCu 4-5

Patients in group 4-5 have by definition function of the BR, wrist extensors and PT, and in group 5 the FCR also. The BR and ECRL are available for transfers, which makes this group well suited for the alphabet procedure (**study II, III, IV**), with active thumb flexion, active finger flexion, and passive extension.

5.5.5 O/OCu 6-8

Patients in group 6-8 have by definition also partial or complete function of finger and thumb extension, and weak flexion of their fingers (group 8). These patients benefit from a customized alphabet procedure. They may get thumb abduction by transfer of extensor digiti minimi to abductor pollicis brevis (EDM-APB) (Fridén et al, 2012) and active interossei (FDS-interossei, according to Stiles-Bunnell) (Bunnell, 1942). An arthrodesis may not be needed if the thumb is stable enough. See algorithm (Figure 23).

5.5.6 O/OCu 9

Patients in group 9 by definition lack only interossei muscles. Reconstruction of active IO as in the previous group may be considered. Spasticity problems are common in this group, which is why spasticity-reducing procedures may be required.

5.5.7 O/Ocu X

Patients in group X have by definition a mixed presentation of functions. Combinations of available surgical techniques can be performed according to the patients' needs.

5.5.8 Spasticity

Patients with incomplete tetraplegia and spasticity (**study V**) are a large group. Spasticity occurs in all classification groups and may be more pronounced unilaterally and focally. When conservative treatment fails the patient may be a good candidate for tendon lengthening, muscle releases, releases of the interossei (**study I**) and ECU tenodesis (**study III**).

Table 6. Algorithm for surgical treatment in tetraplegia.

ICSHT group O/OCu	**Available muscles below elbow**	**Suggested or possible surgical procedure**
0	No muscles	Nerve transfer, Triceps reconstruction
1	BR	BR-ECRB, Passive key grip, Triceps reconstruction
2-3	ECRL, ECRB	BR-ECRB, Passive key grip, Passive IO, Triceps reconstruction, or BR-FPL through IOM
4-5	PT, FCR	**The Alphabet procedure**, Triceps reconstruction
6-8	EDC, Thumb extension, Partial finger flexors	**The Alphabet procedure with options**: EDM-APB, Active IO
9	Lack only IO	Active IO
X	Mixed pattern	Combinations
Spasticity	Mixed pattern	Tendon lengthening, Muscle release, **Distal ulnar intrinsic release, ECU tenodesis**

5.6 Limitations of the Studies

Generally, the sizes of all the groups are small, even though patients are recruited from the whole nation and our unit is internationally one of the largest. The study groups (except study IV) comprise several ICSHT classification groups with variations within and between the groups regarding spasticity and activation patterns. Since the study groups are small, statistical analysis is also limited. Therefore, hypotheses need to be kept simple.

There is a slight overlap of patients in study II-IV, in both study groups and control groups. The number of unique individuals is 112 and not 130 as it appears in the total count of patients belonging to the studies.

The national registry of tetraplegia, comprising more than 800 individuals is a great resource to collect data for controls, but it has its limitations. The tools for assessing grip strength and pinch strength may vary as well as the examiners. COPM was not a standard assessment before, and therefore not available for comparison with new studies. Another limitation for COPM may be that it is not validated in Swedish. It is, however, validated in English.

Patients in study I were divided into 2 groups, mild and severe, depending on the involvement of the MCP joints. Intrinsic tightness was tested with Bunnell's test and the ROM of the PIP joints were increased and demonstrated. The ROM for the MCP joints was also increased, but several of the patients underwent simultaneous surgical procedures, such as tendon lengthening. Since it is difficult to judge whether the increase of ROM in the MCP joints came from intrinsic release or tendon lengthening, no further analysis was made.

The patients in study II came from three different units, and the results of key pinch and grip strength were measured with different instruments by different examiners. The patients were operated on by 4 surgeons.

Study V is limited by itself for being a pilot study. Outcomes of the surgery cannot be evaluated since there were only 8 patients who all had very different degrees of spasticity and surgical procedures performed.

6 SUMMARY

Distal ulnar intrinsic release reduced the intrinsic tightness in all operated fingers and the ROM was improved by 25% and up to 45% in mild and severe cases, respectively. The procedure is simple and valuable to reduce intrinsic tightness and improve hand function and grip control. The procedure can be added to other simultaneous procedures.

ECU-tenodesis corrects radial deviation deformity of the wrist joint. Patients, who had this procedure added to their grip reconstruction, had a grip strength twice as strong as the patients, who had grip reconstruction without ECU-tenodesis. Correction of the wrist deformity enables a more ergonomic use of the hand, which may help prevent shoulder pain, which is common among patients with tetraplegia.

The alphabet procedure reliably provides the patient with active finger and thumb flexion and passive extension of the fingers and thumb, pinch, grasp and release function. Grip strength and opening of the 1st web space were significantly larger in patients, who have undergone the alphabet procedure compared to the traditional grip reconstructions (two-stage procedures). A single-stage combination of procedures (the alphabet procedure) was proven possible. One operation also means one rehabilitation period.

Early active mobilization is particularly important after multiple simultaneous procedures to improve functional outcome and to reduce swelling and the build-up of adhesions.

Electro-goniometry by Biometrics is a feasible instrument to assess spasticity-reducing surgery by measuring joint angular velocity and repetitions per second. Together with COPM, these assessment points can be used to evaluate the outcomes of surgery or other spasticity treatments.

7 CONCLUSION

This thesis reports development and refinement of several surgical techniques that, individually and combined, facilitate the reanimation of grasp control in people with tetraplegia. Rebalancing of the hand by selective release and tendon lengthening techniques enables more favorable mechanical conditions for the forearm, wrist and finger actuators, in patients with tightness and spasticity. Shorter total time in the operation room and for rehabilitation with preserved patient safety enforce the recommendation of applying these techniques.

8 FUTURE PERSPECTIVES

Distal ulnar intrinsic release, ECU-tenodesis, and the alphabet procedure are all implemented in clinic already. Studies for long-term follow-ups would be interesting, but are difficult to engineer. The patients are from the whole nation and extra follow-up visits are extremely sparse. The ECU-tenodesis is thought to be valuable of ergonomic reasons. 59% of individuals with tetraplegia have shoulder pain (Curtis et al, 1999), which is why this link would be interesting to further investigate. Patients with both complete and incomplete tetraplegia often have wrist radial deformity. If the ECRL is stronger or more spastic than the ECRB the result is radial deviation (the ECU is paralyzed). When transferring the ECRL to the FDP index-ring finger, the ECRL gets a different moment arm than before. How much or whether this transfer affects wrist deviation is not clear and would be interesting to clarify with biomechanical studies.

As long as stem cells or any other treatment for spinal cord injuries are not available, it is important to continue developing surgical reconstruction of hand and arm function. We do not know as of yet whether stem cells will be the future treatment for spinal cord injuries.

Several patients are not satisfied with the CMC-joint arthrodesis, which is important for stabilization of the thumb to enable a good grip. Another stabilization method should be taken into consideration.

According to recent literature (Wolfe et al, 2011) contraindications to surgery in tetraplegia are spasticity, contractures, chronic pain problems and psychological instability. We have pushed the limits for surgery and it is only the last mentioned issue that is still a contraindication in our unit. Spasticity-reducing surgery is frequently performed. The pilot study of electro-goniometry as a spasticity assessment is promising and should be designed for a larger study in which outcomes of spasticity-reducing surgery can be evaluated. A study with long-term follow-ups is necessary and to further differentiate between the various spasticity patterns to better predict the outcomes. The clinical impression is that patients with focal spasticity do better than patients with general spasticity.

The ICSHT Classification only describes muscles with a grade of 4 or 5. We have used deltoids of grade M3 for triceps reconstructions and EDM of M3 for EDM-APB transfer with successful results. Perhaps it is time to reconsider what can be used. Electro-stimulation may increase muscle strength 1 grade, which will push the limits for further development and selection of candidates for surgery.

Combining multiple surgical procedures simultaneously is not only more convenient for the patient, but also cost-efficient. The complication rate is low and the patient safety is maintained. Cutting down on one operation and one rehabilitation period means 10 days less hospital care and fewer visits to the outpatient clinic. Considering that this counts per limb, the sum that is saved per patient is huge. Another aspect is the higher degree of autonomy and hand function the patients achieve by surgical restoration. Being able to do more by themselves mean less need of personal assistance. Some patients have gone back to a part-time job due to better hand function. The socioeconomic profits are probably enormous. Health economic studies in this field would be very interesting to conduct.

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APPENDIX