Functional reconstruction of the hand after peripheral nerve lesions

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Mister president

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もうしわけありませんがわたしは

にほんごがはなせません。

なのでえいごではなします。

A message written by my daughter's Japanese teacher

SHINAI NAR YÛ JIN HE
SHINAI NARU DÔRYÔ HE
MÔSHIWAKE ARIMASEN GA WATASHIWA NIHON GO HANASE MASEN
NANODE EIGO DE HANASHIMASU

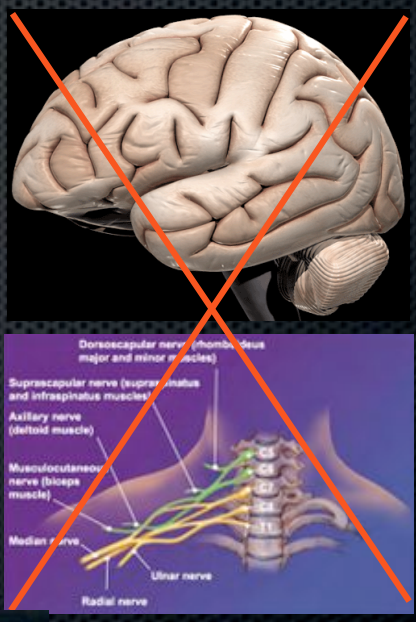
Questions ?

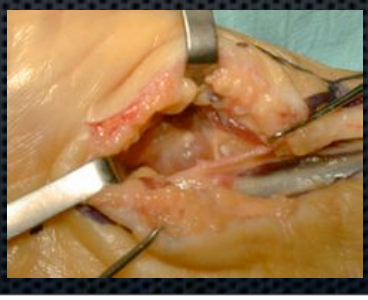
- Which peripheral nerve lesions may we reconstruct ?
- What means “functional reconstruction” ?
- What are the hand functions we want to reconstruct ?
  - What are we talking about ?

What are we talking about ?. What does mean functional reconstruction of the hand after peripheral nerve lesion ? i.e. which functions of the hand do we want to reconstruct, with which techniques and in which cases ?

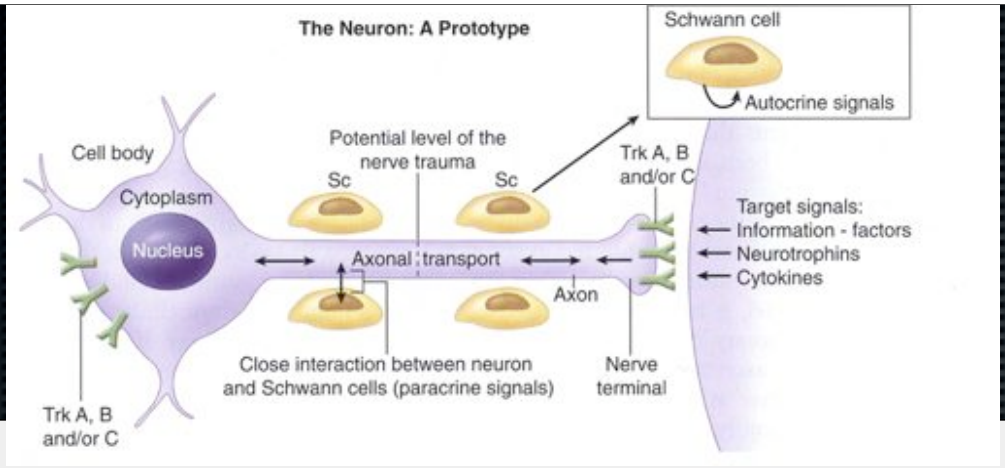
Peripheral nerve lesions ?

- Lesion on the main nerve trunks for the hand
  - Not a brain/medullary lesion
  - Not a brachial plexus lesion
- Median / ulnar / Radial nerve injury
- Compression or section of the nerve





Hand paralysis due to brain injury, cord injury or even brachial plexus injuries are not considered peripheral nerve lesions.
In clinical practice, we are talking about lesions of the median, ulnar or radial nerve which are, by far, the most important nerve for hand function.
A nerve lesion may be due to nerve compression or to a partial or complete nerve division.



Classification of Nerve Injury

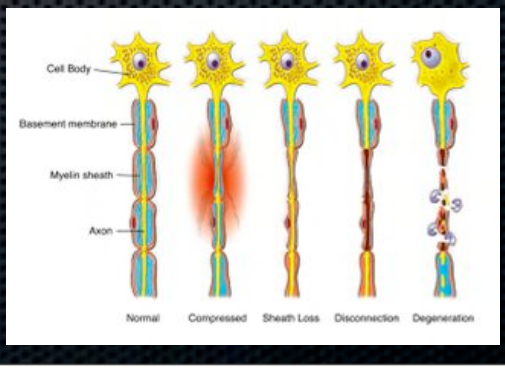
Sunderland	Seddon	Mackinnon	Injury
Degree I	Neurapraxia	Degree I	Conduction block, resolves spontaneously
Degree II	Axonotmesis	Degree II	Axonal rupture without interruption of the basal lamina tubes
Degree III		Degree III	Rupture of both axons and basal lamina tubes, some scar
Degree IV		Degree IV	Complete scar block
Degree V	Neurotmesis	Degree V	Complete transection
		Degree VI	Combination of I–V and normal fascicles

- Stage 1 and 2 should recover spontaneously
- Only stage 3 and above in Sunderland's classification will need some type of repair

Among nerve lesions, not all injuries will end up with reconstruction. According to Sunderland and Seddon's classification neurapraxia (first degree) is a self-limiting injury that recovers spontaneously. A second-degree injury involves axonal rupture (axonotmesis) without interruption of the basal lamina tubes. These lesions also recover spontaneously at the classic rate of 1 mm per day

Nerve compression

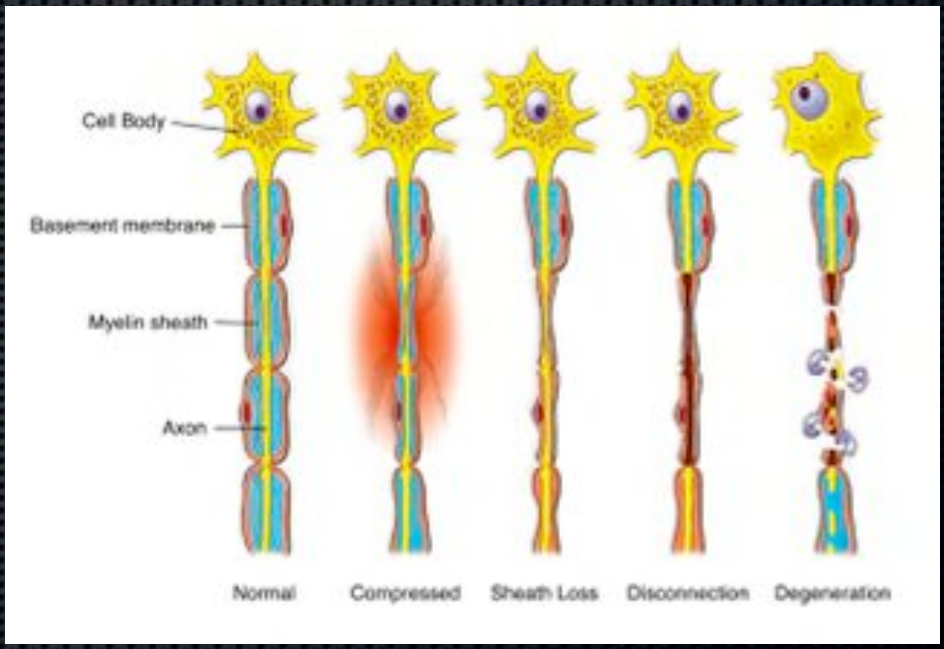
- About 2,4 million consultations/year in the USA are for carpal tunnel
- About 80,000-100,000 carpal tunnel release in France every year (surgical fee = 115 € /160$/10,000 ¥)
- Medical costs > loss of production



Nerve compressions are very frequent and very costly to our societies as most of the cost is due to medical care (consultation, surgeons' fees, etc.).
Impairment is usually limited and there are few indications for functional reconstruction.

Pathophysiology of nerve compression

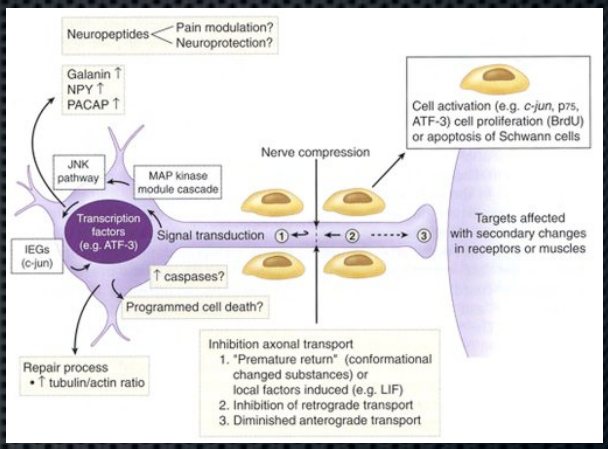
- Demyelination due to Schwann cell necrosis and apoptosis
- Axonal pathology

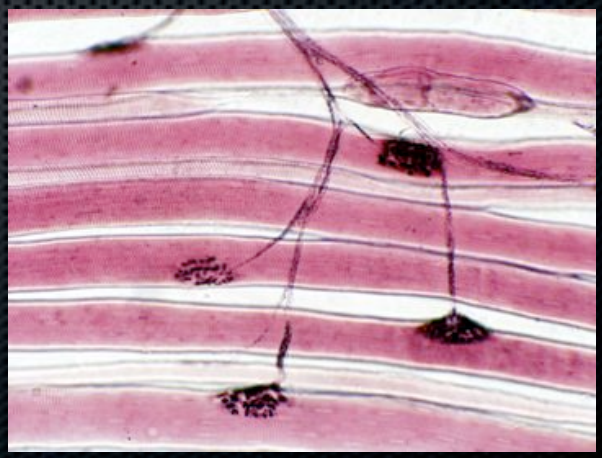


With long-standing evolution of compression, Schwann cell will die (demyelination), and even the axon may degenerate.

Pathophysiology of nerve compression

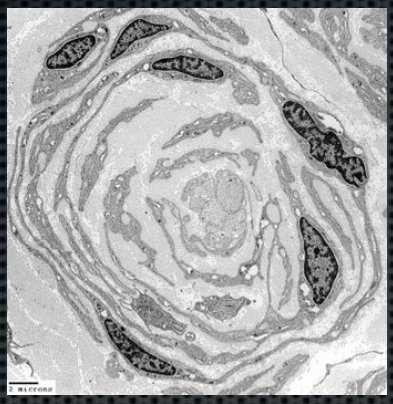
- Alteration of the cell body (incomplete recovery)
- Motor-end plate degeneration (muscle atrophy)





In that case, we will observe changes both in the proximal cell body which may explain incomplete recovery after surgical release and in the motor-end plate with subsequent muscle atrophy that can be permanent and responsible for a paralysis .

Pathophysiology of nerve compression



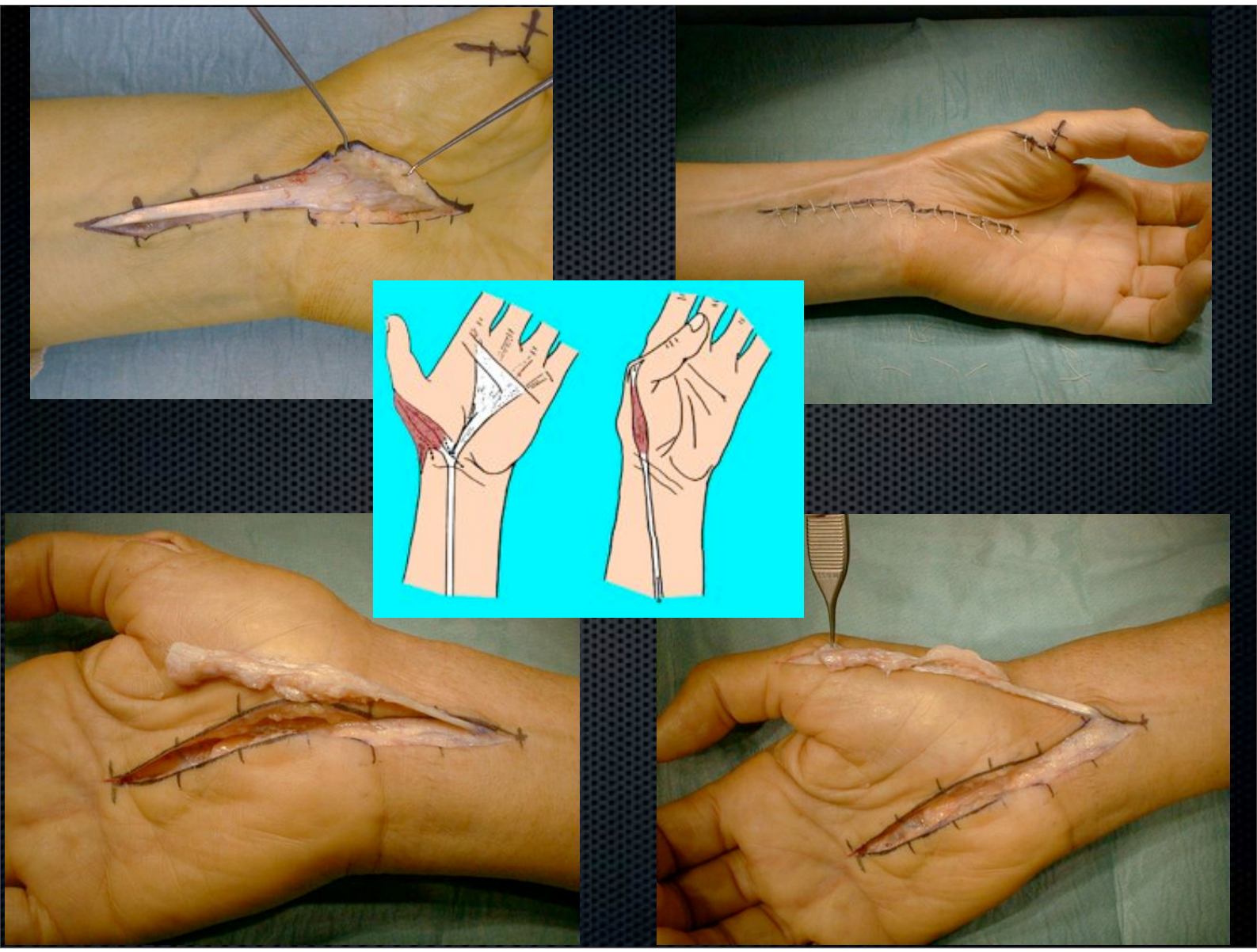
- The lamina is intact (Myelinated/non-myelinated axons)
- Potential for (some) recovery after nerve release due to axonal re-growth to the right nerve-endings by using existing precise pathways

However in nerve compression injury, whether acute or chronic, the basal lamina is intact and axons may re-growth to their correct nerve-endings.

Functional reconstruction

- Will only be indicated in the most severe lesions
- 6% of more than 1500 CTS (Foucher 1991)
- Matsuzaki (2004) reported functional improvement in 15 patients with 4,5 years follow-up in ulnar tunnel entrapment with muscle atrophy

This is why functional reconstruction is very rarely needed. Functional reconstruction after carpal tunnel surgery have been proposed but most series were made more than twenty years ago. A recent publication by Matsuzaki suggested that even in long-standing ulnar tunnel syndrome, patients improved with long-term follow-up without additional surgery.



There is a plethora of opponensplasties described in the literature but if reconstruction is needed for a long-standing carpal tunnel surgery, the Camitz palmaris longus opponensplasty is uniquely suited. It is simple to perform, and has a negligible donor deficit. In that case it was even more easy as the patient had a Dupuytren's disease which make the donor tendon stronger than usual.

Results

- Foucher 1991: 73 Camitz opponensplasty with > 90% good results (good antepulsion and/or pronation)
- Richer 2005: 50 FDS transfer 100% improvement

The largest series for Camitz's opponensplasty reported good results in a majority of patients. Recently a large series of FDS transfer also reported improvement in every patients.

Nerve compression in leprosy

- Third world countries
- Late presentation with severe sequelae + intra-neural pathology
- Many indications for functional reconstruction

There is however many indications for hand reconstruction in Leprosy which is a particular infectious disease, with both intra-neural pathology and nerve compression. Leprosy is rarely seen in our countries to date.

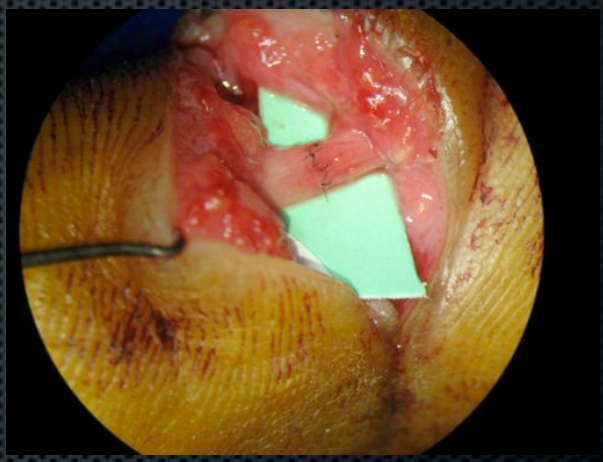
Nerve transsection

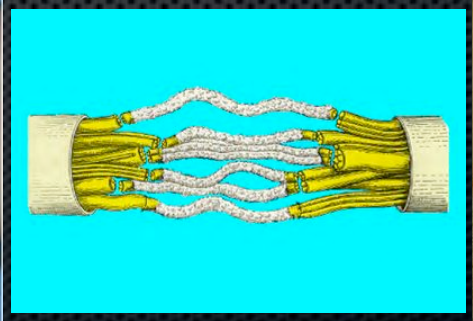
- About 3% of hand injuries
- Costly
  - median nerve section at the forearm costs about 51,000 € (71,000 $) with 90% of costs due to loss of production (Lundborg)
- Most patients will loose their job due to functional limitations

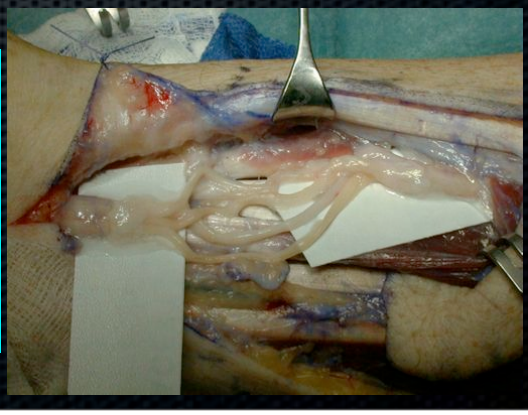
Nerve section on the contrary are less frequent and are usually seen in young male adults. They are costly both for our societies, most of the total cost being due to loss of production and for the patients as most of them will end up with functional limitations.

What to do after a nerve injury ?

- Repair it !
- Primary (or secondary) repair is by far the best technique using suture techniques, nerve grafts, nerve conduits,...







After a nerve division, nerve repair either early or late is by far the best technique for restoration of a functional hand whatever the technique used.

What to do after a nerve injury ?

- However it can be technically impossible or physiologically not useful to patients
  - Functional reconstruction may be a solution

However there are cases where it is either impossible or not logical to do a nerve repair. In those cases, functional reconstruction is the only solution.

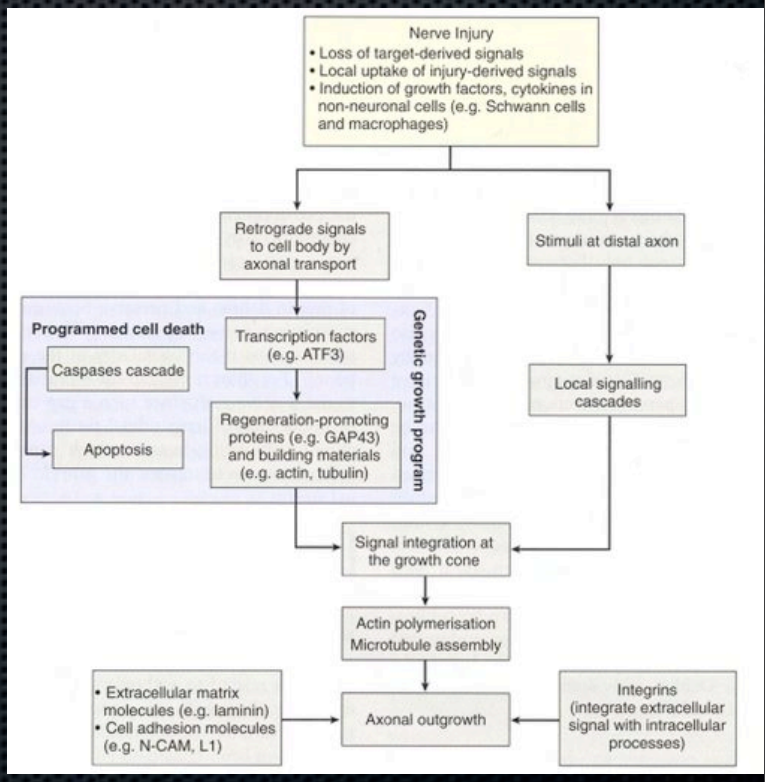
When is nerve repair impossible ?

- Failure of repair
- Physiological limitations
  - Technically possible but will fail
- Technical limitations

Why a patient with a nerve repair will need reconstruction ? First if repair was a failure, or if repair can be done but would give bad results or if nerve repair is technically impossible.

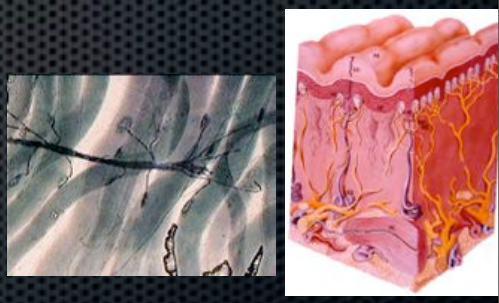
Failure of repair

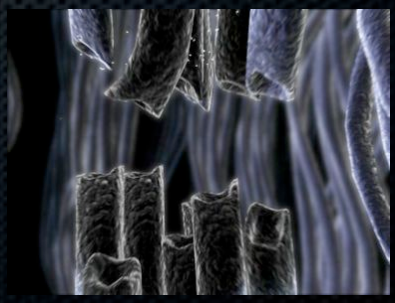
- After nerve repair, there are a number of modifications from the brain to the end-plate/ sensory receptors that may explain why even a “perfect” repair may fail



After a nerve repair there are major changes from the brain to the end plate that explain why some repair may fail

- Modification of cortical representation
- Neurons die from apoptosis (up to 50%)
- Nerve re-growth after wallerian degeneration is limited in time (repair within 6 months)
- Changes in distal receptors may become irreversible (12-18 months)
- Axonal misdirection after repair
  - Preferential motor regeneration ? (Brushart, 1988)
  - Preferential sensory regeneration ? (Maki, 1996)





Here is list of some of the modifications that are observed: brain changes, death of neurons up to 50% in experimental studies, limited capacity of regeneration with time, changes in distal receptors that become irreversible and misdirection of repair

Factors influencing outcome after nerve repair ?

- Meta-analysis (623 median/ulnar nerve injuries - Ruijs 2005)
- Motor and sensory recovery were significantly associated (Spearman $r = 0.62$, $p < 0.001$).
- Multivariate logistic regression analysis showed:
  - Age (< 16 years versus > 40 years: odds ratio, 4.3; 95 percent confidence interval, 1.6 to 11.2),
  - Site (proximal versus distal: odds ratio, 0.46; 95 percent confidence interval, 0.20 to 1.10),
  - Delay (per month: odds ratio, 0.94; 95 percent confidence interval, 0.90 to 0.98).

There are also local and physiological reasons to explain a frustrating result after nerve repair. In a recent meta-analysis, main factors to explain a poor results were advanced age, a proximal lesion or a long delay before repair

Factors influencing outcome after nerve repair ?

- For sensory recovery, age (odds ratio, 27.0; 95 percent confidence interval, 9.4 to 77.6) and delay (per month: odds ratio, 0.92; 95 percent confidence interval, 0.87 to 0.98) were found to be significant predictors.
- In ulnar nerve injuries, the chance of motor recovery was 71 percent lower than in median nerve injuries (odds ratio, 0.29; 95 percent confidence interval, 0.15 to 0.55).

- No evidence that any technique (epineurial suture, fascicular suture,...) results in improved functional outcome (Lundborg, 2004)

These factors were identical for sensory reconvery.
The ulnar nerve repair had also poorer results compared to median nerve repair. However the technique has little influence.

When is nerve repair impossible ?

- Physiological limitations
  - Patient's age, site of injury, size of nerve loss or poor local conditions for nerve grafts
- Technical limitations
  - No distal stump available for suturing
  - Definitive atrophy of motor end-plates (> 12-18 months)
  - Partial recovery after nerve repair or partial nerve lesions or no clinical/EMG progression 1 year after repair

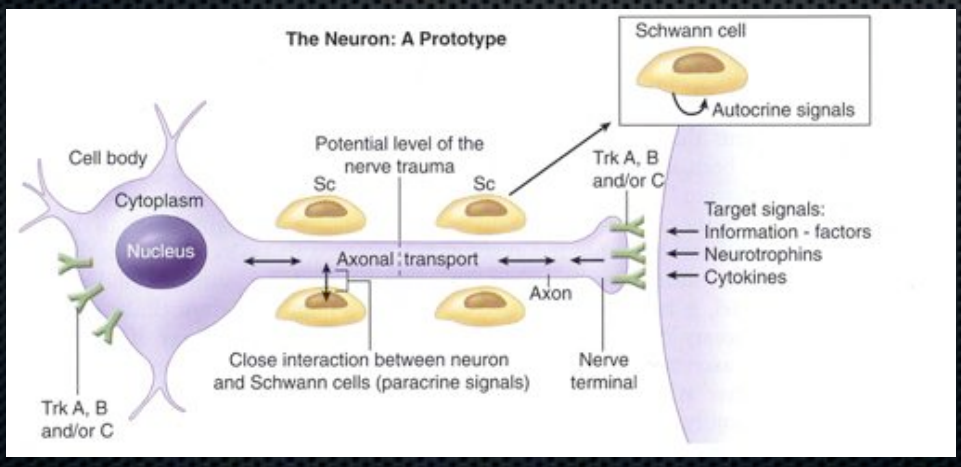
In some patients, event if possible nerve repair may not be performed for those physiological reasons as a poor result is to be expected
Sometimes it is even impossible to perform a nerve repair

What are the hand functions ?

What are the hand functions we want to reconstruct ?

Functions of the hand

- A sensory organ
- A working tool
  - Dependent of a normal nervous system



The hand has two main functions. It is a sensory organ and a working tool. Both functions are dependent of a normal nervous system.

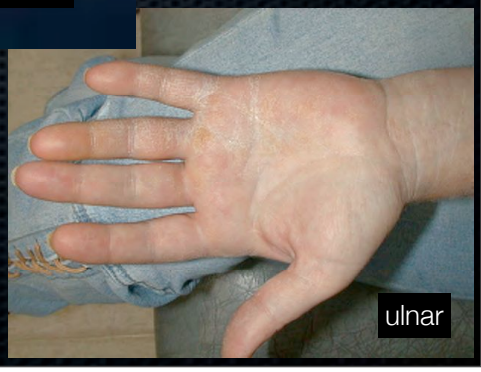
Functions of the hand

- Nerves also carry pain and sympathetic fibers
- Functional reconstruction means giving the patient the possibility of using:
  - A painless hand
  - A sensitive hand to feel the environment

But apart those two main functions, nerves also carry pain information and sympathetic fibers.

“Sympathetic” repair ?

- To date we have absolutely no possibility of repair
- Can be very disabling
  - Cold intolerance
  - Dysesthesiae
  - Sudomotor, Hair changes ...
- Medical treatment (?)



To date we are unable to reconstruct the function of the sympathetic fibers and loss of that function may be very disabling to certain patients

Pain

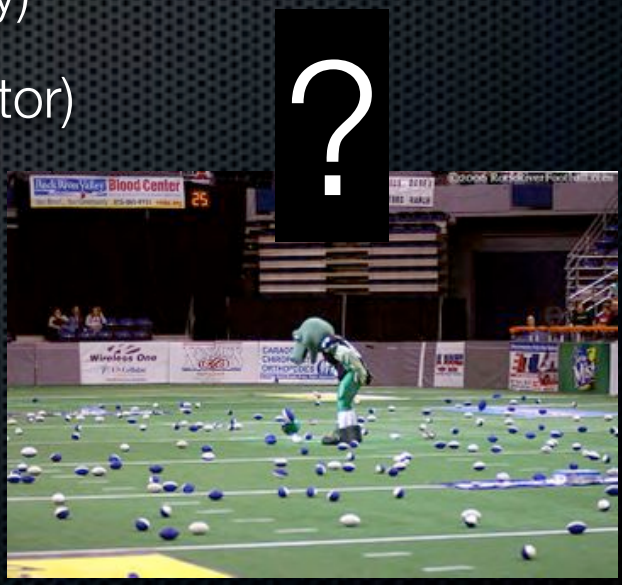
- Two types of pain
  - De-afferentation : No surgery, only pain clinic
  - Painful neuroma: If pain clinic and rehabilitation fails, surgery can be indicated (see: Nath 1996)

I will not discuss pain treatment but after a nerve injury, two types of pain can be seen. Only neuromas are amenable to surgery if medical treatment fails.

Functional reconstruction

Sensory or Motor

- Innervated flap transfer (Sensory)
- Nerve transfer (sensory and motor)
- Direct neurotization (motor)
- Tendon transfer (Motor)



To improve the hand sensory or motor function, there are new techniques that have emerged in the last ten years especially nerve transfers. Tendon transfers are well-known and will be discuss at the end of the conference.

Functional sensory reconstruction

I will start by the functional reconstruction of sensibility.

The sensational hand

- Enormous capacity to perceive, to execute and to express, simultaneously, in the act of touch (Gibson, 1962)

Why is this so important ? The enormous amount of sensory receptors in the hand makes the hand a sense organ. The hand has the capacity to perceive, execute and express in the act of touch.

The sensational hand

- “Tactile gnosis” (Möberg 1958) illustrates the interplay between peripheral sensory functions of the hand and the interpretation of sensory impressions in the brain
- Feed-back between hand and brain is a pre-requisite for regulation of grip strength and grip speed (Johansson, 2002)

Möberg had called tactile gnosis the interpretation by the brain of the sensory informations given by the hand.
For a good motor function, there is a need for a good sensibility to obtain a sensory feed-back o hold objects.

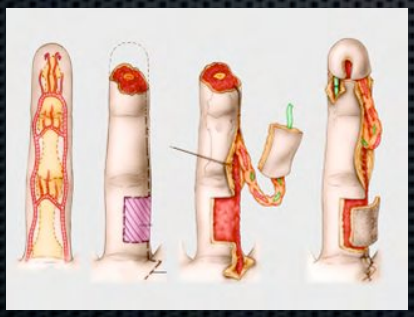
Sensory reconstruction

- Innervated flaps
  - Local / Regional (pedicled)/ Free flaps
  - For median nerve territory only
- Nerve transfer
  - Median to ulnar, ulnar to median, radial to median

Sensory reconstruction of the hand can be done by two ways. Either by mobilizing an innervated skin flap to the denervated area, or by using nerve transfer. Innervated flaps can be either local, pedicled or free flaps

Innervated Local flaps

- Most are used for pulp injuries (all type of innervated flaps can be used)



Innervated local flaps can only be used for pulp injuries when there is no distal stump available either in emergency or after healing.

Innervated Local flaps

- Only for distal digital nerve injuries
  - Advancement of an innervated Venkataswami's flap to cover the defect and treat a neuroma (Foucher 1991)

In chronic cases, advancement of an innervated flap may be used to cover a nerve defect or treat a neuroma as proposed by Foucher.

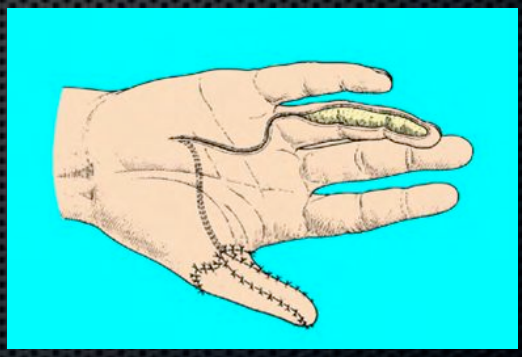
Hetero-digital flaps

- Described by Littler
- Only for median nerve injuries
- Transfer of a pedicled flap from a sensible finger when ulnar nerve is intact (w/wo nerve division/suture)

The hetero-digital flap was first described by Littler. One will move the flap from an innervated area to a denervated one, like in this case were we move a flap to reinnervated the pulp of a thumb covered with a radial forearm flap.

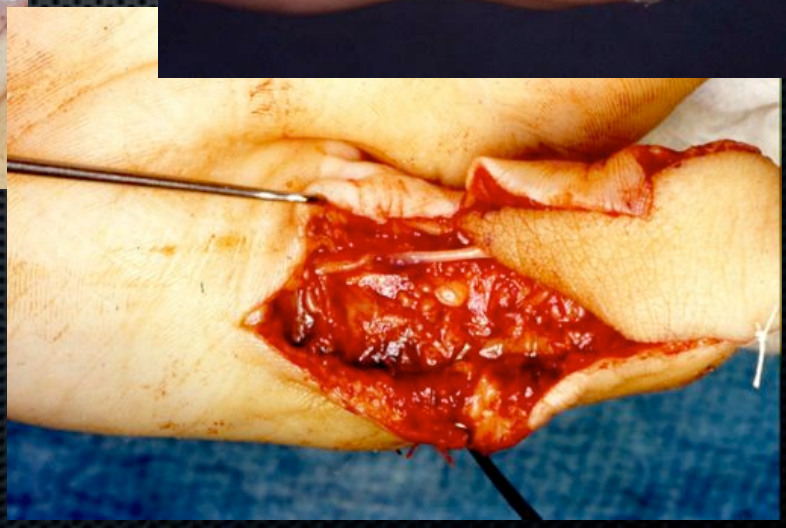
Hetero-digital flaps

- Few indications due to sequelae of donor finger
- Adani 1990 (9 cases), Kumta 1997 (17 cases), Oka 2000 (21 cases)
- Numbness when flap is touched, 9 mm 2PD, double sensation and poor sensory switching from the donor to recipient site



However indications are rare due to the importance of sequelae on the donor finger and the poor results obtained, whether or not a nerve debranching technique was used. Oka recently published a large series with limited results.

Hetero-digital flaps

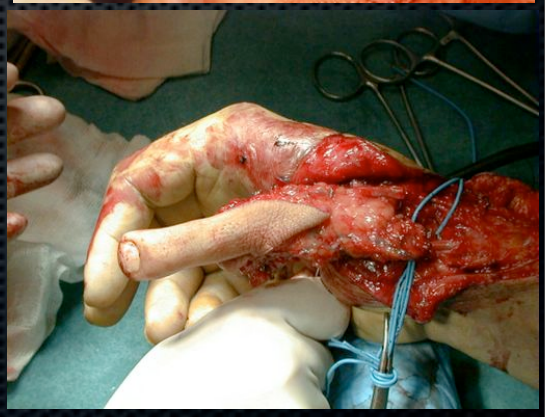


- Reinnervated kite flap

Other flaps can be used like this reinnervated kite flap but they have even poorer results.

Reinnervated free flaps

- For “median nerve” injuries
- From the foot (Daniel 1976, Ohmori 1976, Minami 1984; Kato 1989) as 1st web space flap and/or toe transfer



Not specifically designed for nerve reconstruction

Free flaps from the foot have been largely used, especially in asiatic countries but they are in fact more used for thumb reconstruction than for reinnervation. They are actually limited to thumb and distal pulp reconstruction and suppose an intact median nerve at the wrist.

Reinnervated free flaps

- Thenar free flap (Omokawa 1996)

Omokawa presented the use of a re-innervated thenar free flap that has also the same limitations and like other flaps can only be used when there is no distal nerve stump but a good proximal nerve stump at the wrist hic is not so frequent

Nerve transfer

- New technique, no series (Veber 2004)
- Criteria ?

TABLE 3

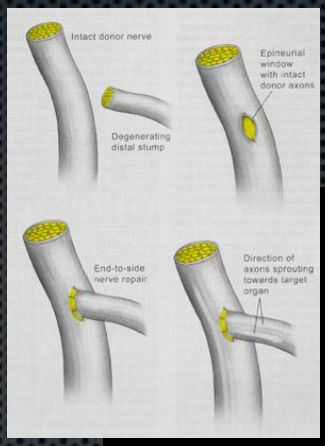
Criteria for Sensory Nerve Transfer

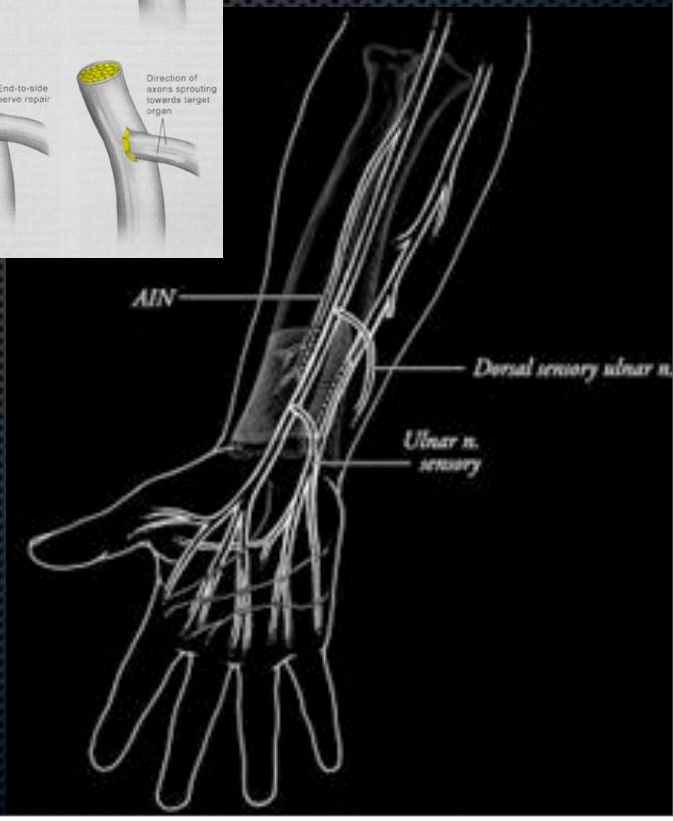
Donor sensory nerve near the target sensory nerve
Expendable donor sensory nerve (noncritical sensory distribution)
Donor sensory nerve with a large number of pure sensory axons
Denervated distal end of donor nerve repaired end-to-side to adjacent normal sensory nerve
Sensory re-education improves functional recovery

Nerve transfer for sensory re-innervation is a new technique inspired by surgical procedures developed for brachial plexus surgery. Indications are rare and, to date, there are no series but only case reports with no detailed results.

Sensory re-innervation of the ulnar nerve

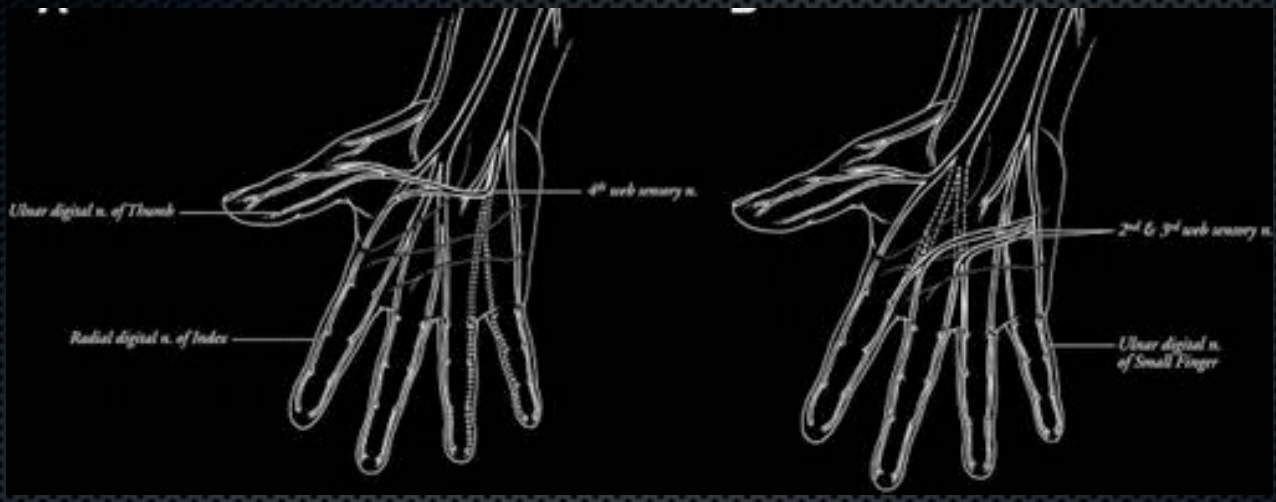
- End-to-end transfer of the third web space nerve to the ulnar nerve (Lewis 1984)
- End-to-side nerve transfer on the median nerve
  - Unpredictable results





For the ulnar nerve, Lewis was the first to published of 5 patients with excellent results by transferring the nerve of the third web space to the sensory branches of the ulnar nerve but this has not been reproduced yet.
Some attempts have been made using the ulnar nerve, both volar and dorsal branches, that are anastomosed end-to-side to the median nerve at the forearm level. However end-to-side techniques has not yet proven to be as reliable as end-to-end suture technique.

Sensory re-innervation of the median nerve



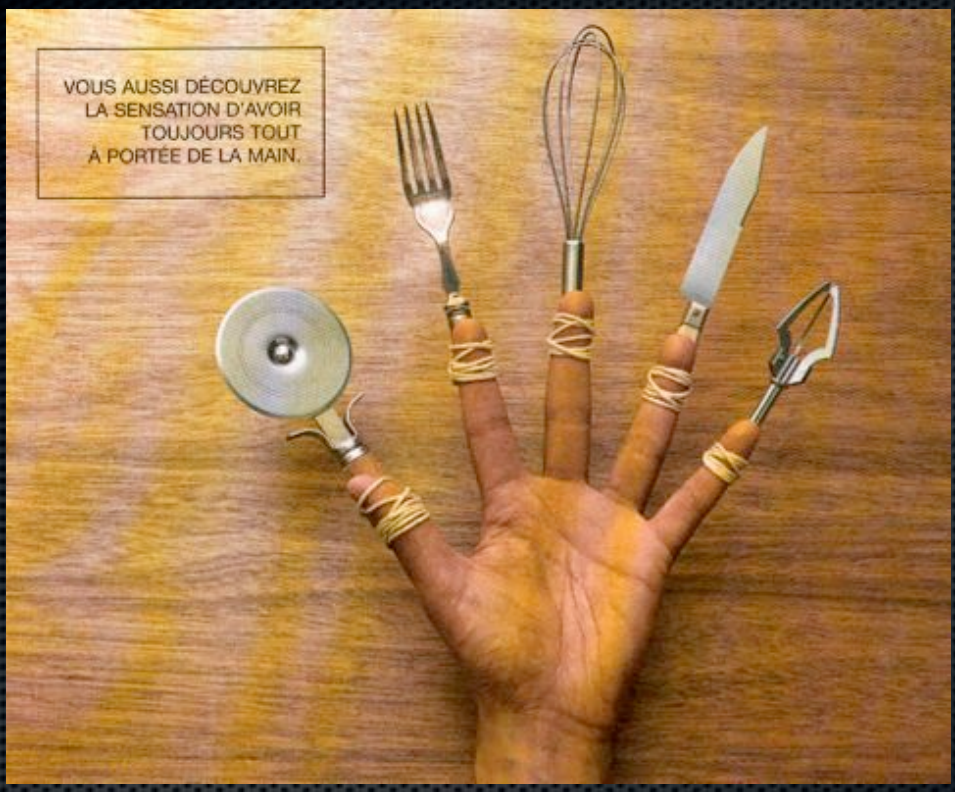
- Ulnar side of thumb, radial side of index
- Many attempts using radial and/or ulnar nerve fascicles (Humphreys 2002) sutured with an end-to-side technique to the branches of median nerve

If the median nerve is injured, then the common digital nerve from the fourth web space supplied by the ulnar nerve, the dorsal sensory branch of the ulnar nerve, and the sensory radial nerve can all serve as donor nerves. The remaining common digital nerve(s) are coapted end-to-side into the ulnar or radial nerves.

Sensory reconstruction ?

- Many attempts
- Many interesting ideas
- Few interesting (functional) results to date
  - May be worth trying in certain cases

To conclude for sensory reconstruction, results to date are not spectacular, leaving patients with severe sequelae that impaired their hand function. However sensory reconstruction is worth trying to limit the sequelae and improvements will be made in the future I hope.



Functional motor reconstruction

What about motor reconstruction. Can we help our patients ?

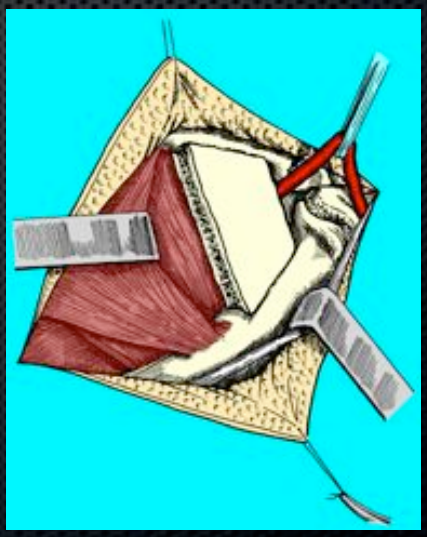
Motor reconstruction ?

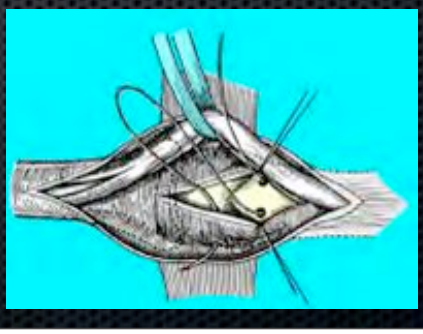
- Arthrodesis (joint stabilization, rarely done)
- Tenodesis (rare indications)
- Direct neurotization
- Nerve transfer
- Tendon transfer

Many techniques are available, from passive like tenodesis or joint stabilization to active nerve repair or palliative tendon transfers.

Joint stabilization

- Arthrodesis may be needed in severe cases but is usually avoided (lost of the tenodesis effect).
- Ligamentous repair may be needed before tendon transfer
- Capsulodesis can help in lax patients





Joint stabilization is very important for hand function and in some cases it is the only technique that will be used like some arthrodesis for the paralytic thumb

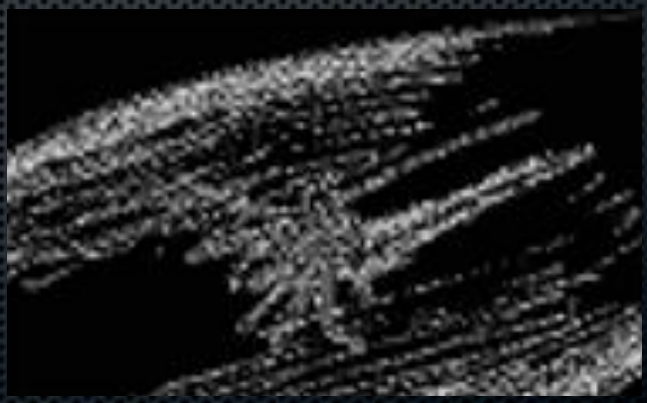
Tenodesis

- Only done in very severe cases when there is not enough transfer to use
- Passive function

Tenodesis are very rarely done for peripheral nerve lesion and have been discussed by Caroline Leclercq in her presentation

Direct neurotization

- Early 20th century (Heineke 1914; Erlacher 1914; Steindler 1915,...) mainly done for poliomyelitis with poor results



Direct neurotization is not a new idea but was abandoned in the 50's. It consists to place a motor nerve stump divided in small branches directly into a denervated muscle.

Direct neurotization

- No published series
- 72% good to excellent results according to Brunelli over 200 cases collected in the literature

	Nb cases	>M4	M3	<M3
Extensor forearm muscles	17	11	2	0
Biceps	8	4	3	
Thenar muscles	4	3	1	
Total	65	37	6	1
Other studies	206	106	29	32

Brunelli reported good results from his series of 65 cases and from a literature review of over 200 cases. However this technique has not gained a large diffusion.

Nerve transfer

- Some attempts have been made
- Principles are very similar for motor and sensory nerve transfers

TABLE 2

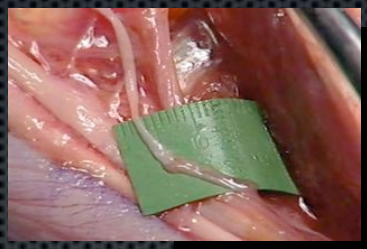
Criteria for Motor Nerve Transfer

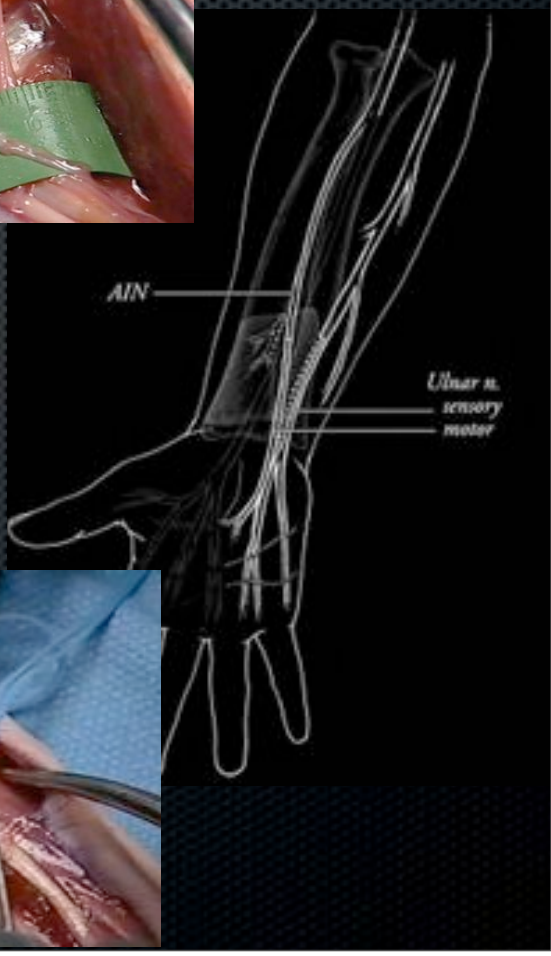
Donor nerve near motor end plates of target muscle (shortest distance = shortest time for reinnervation)
Expendable or redundant donor motor nerve
Donor nerve with pure motor nerve fibers
Donor motor nerve with a large number of motor axons
Donor nerve innervates a muscle that is synergistic to the target muscle (preferred but not required to facilitate re-education)
Motor re-education improves functional recovery

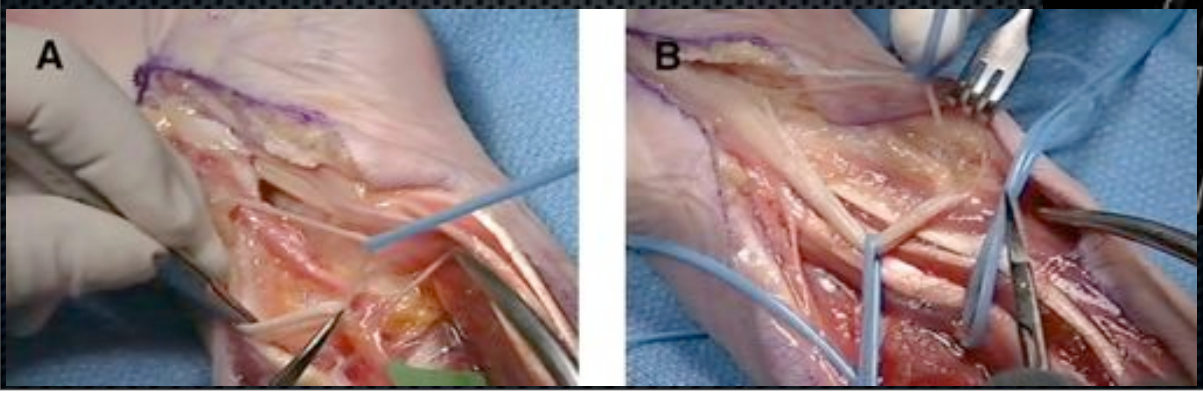
There are many theoretical advantages of a nerve transfer over that of a tendon transfer:
- a nerve transfer offers the capacity for restoring sensibility in addition to motor function, this is purely theoretical as most attempts were done for purely motor reconstruction
- multiple muscle groups can be restored with a single nerve transfer in proximal lesions
- The insertion and attachments of the muscle(s) in question are not disrupted.

Motor nerve transfer

- Terminal branch of anterior interosseous nerve to deep motor branch of ulnar nerve (Wang & Zu 1997, Battiston 1999, Novak 2002, Wood 2004)



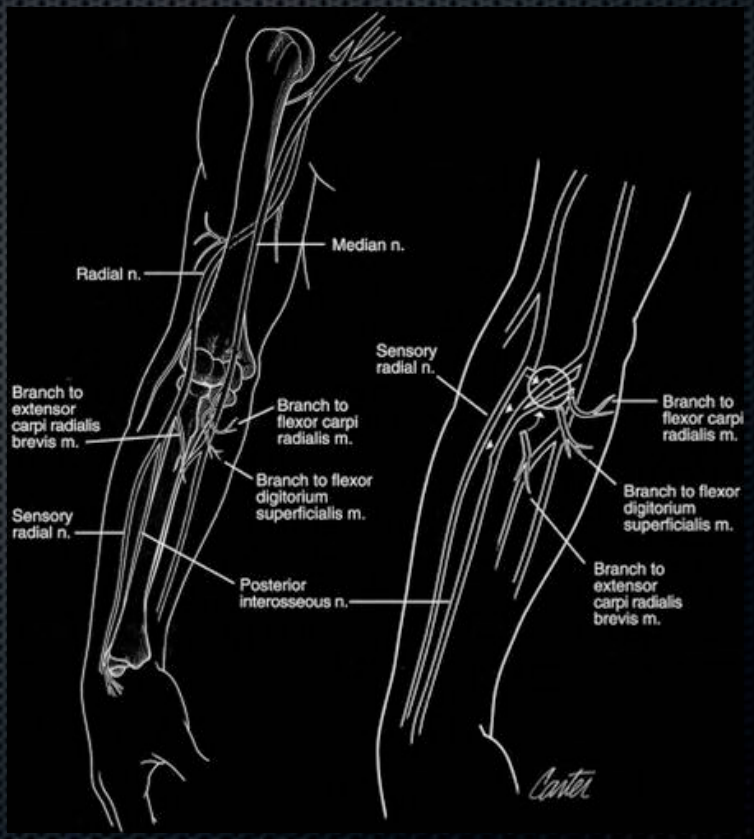




Different motor nerve transfer have been done for hand reconstruction. The distal branch of the anterior interosseous nerve was used to to be transferred to the ulnar motor branch.

Motor nerve transfer

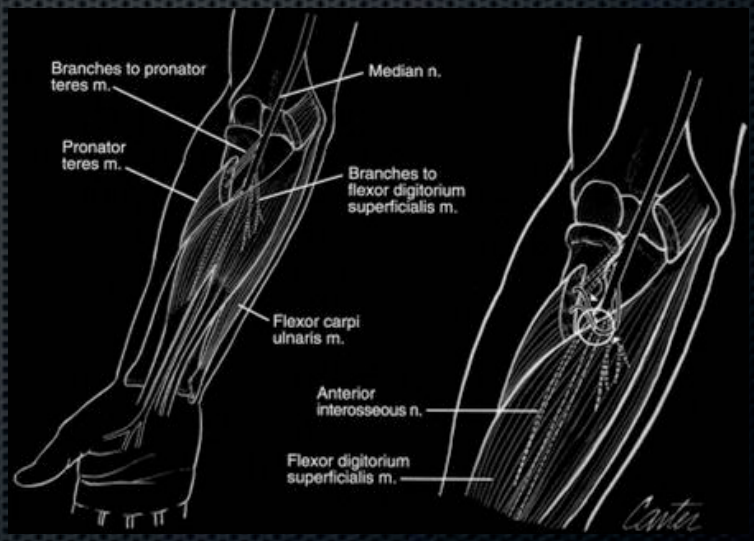
- Median nerve (FCR) to radial nerve at the elbow (Mackinnon 1999)



Some fascicles from the median were transferred at the elbow to the posterior interosseous nerve.

Motor nerve transfer

- Radial nerve to median nerve (Mackinnon 2000)



And the distal motor branches of the radial nerve were used to re-innervate the median nerve at the elbow

Nerve transfer

- No series, some improvement is claimed
- May be worth trying in some rare cases

However, to date no series are available and published results only shown “some improvements” as preventing the need for a tendon transfer or limiting clawing of an ulnar hand

Tendon transfer is still the mostly used technique for motor reconstruction

With the help of Caroline Leclercq

So tendon transfers are by far the mostly used technique.

Principles

- Each patient is unique
- Many options are available
- Many textbooks describe the techniques with details and highlights the principles (*Tsuge, Principles and Practices of Hand Surgery)*

- Do not be harmful !
  - Know what to do
  - Know what can be done
  - Know what you can do

Many tendon transfers have been designed and indications must be weighted for a single patient with the help of more experienced colleagues that will help you to balance between the gain in function you expect that must outweight the created deficit. There are some important principles to remember that are available in many textbooks on tendon transfer

Principles (2)

- Take great care of soft tissue equilibrium
  - Good skin coverage (need a flap before transfer ?)
  - Mobile joints (arthrolysis ?)
  - Stable joints (stabilization ?)
  - Stable skeletal alignment

among these principles, soft tissue equilibrium is one of the most important. The joint to be move must be supple (arthrolysis may be needed) and stable, the path must be free and soft-tissue reconstruction may be needed prior to tendon transfer as most of the transferred tendon is devascularized and must be considered as a graft.

Principles (3)

- Choose a motor muscle with the right strength
- Choose a motor muscle with the right amplitude :
  - Wrist tendons 33 mm - Finger extensors: 50 mm, Finger flexors: 70 mm
- Choose a muscle of grade 4+ or more
- Forget agonism/antagonism

Table 1 Relative strength of muscles in the hand and forearm, taking FCR = 1

Muscle	Strength relative to FCR
Brachioradialis	2.0
Flexor carpi ulnaris	2.0
ECRL, ECRB, ECU, PT, FPL, FDS, FDP	1.0 (each tendon)
EDC, EIP, EDQ	0.5 (each tendon)
APL, EPB, PL	0.1 (each tendon)
Interossei	2.7 (total/combined)
Lumbricals	0.5 (total/combined)

Reproduced from Gelberman RH. Operative Nerve Repair and Reconstruction. Philadelphia: Lippincott, 1991; 1587, with permission.

Table 2 Excursion of muscles in the adult forearm and hand

Muscle	Excursion (cm)
Brachioradialis	4.0
Flexor digitorum profundus (FDP)	7.0
Flexor digitorum superficialis (FDS)	6.5
Extensor pollicis longus (EPL)	6.0
Extensor digitorum communis (EDC)	5.0
Extensor indicis propius (EIP)	5.0
Flexor pollicis longus (FPL)	5.0
Flexor carpi ulnaris (FCU)	3.0
Flexor carpi radialis (FCR)	3.0
Extensor carpi radialis longus (ECRL)	3.0
Extensor carpi radialis brevis (ECRB)	3.0
Extensor carpi ulnaris (ECU)	3.0
Extensor pollicis brevis (EPB)	3.0
Abductor pollicis longus (APL)	3.0
Lumbrical	3.8
Thenar muscles	3.8
Interossei	2.0

Reproduced from Gelberman RH. Operative Nerve Repair and Reconstruction. Philadelphia: Lippincott, 1991; 1587, with permission.

One must choose a powerful muscle as mechanical conditions will limit its final power. When choosing a motor muscle, one should know its strength and amplitude and Brand's paper in 81 is still a reference (JHS 1981).

Principles (4)

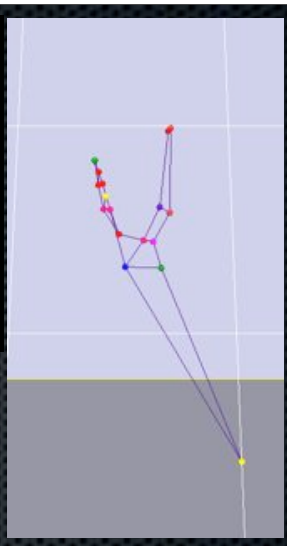
- Choose the straightest trajectory
- Cross only one joint
- Avoid sharp angles in the path of the transfer
- Adequate distal fixation (resistant but non adherent and non-ischemic)
- Adequate tensioning (Goldner “60% length”; Cooney; Experience)
- Rehabilitation (compliance ?)

The straightest path is always preferential although it is sometimes necessary to change the tendon direction, usually around a pulley. Passing through the interosseous membrane may be preferential than going around a forearm bone.
Some authors have described tricks to tension a transfer but experience is probably more important

L.J. Goldner described a practical technique to determine tension for the muscle-tendon unit to be transferred. In the paralyzed extremity, with a tourniquet in place, position the extremity and the recipient tendon in functional position and the transfer tendon in resting length. Traction is applied to the transferred tendon and distance is recorded in centimeters and marked in the wound. Sixty percent of the distance should be marked between the resting length and traction length, and that is the position of the transferred muscle when the final insertion of the transferred tendon is initiated.

Cooney also has reported an per-operative technique to determine tension. The distance that a muscle contracts after release from its normal insertion is measured. The lost length is restored at the time of transfer, plus slightly more tension to pick-up the connective tissue elasticity within the muscle.

Strategy



- One tendon can only repair one function
- Choose tendon according to patient's needs
- Select the most important function to repair first and add additional procedures (joint fusion, tenodesis,...)

In the normal forearm and hand there are 50 muscles to activate movement. The choice is made on the basis of the available possibilities and the demands

Finally your strategy must taken into account the relative importance of each function: essential for forearm and hand function are wrist extension and finger flexion as well as thumb and intrinsic function.
I cannot discuss all tendon transfer for hand reconstruction but I would like to illustrate those principles for some major nerve reconstruction.

Radial nerve

Radial nerve first

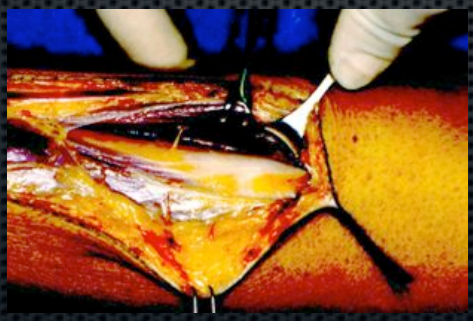
Radial nerve function to restore

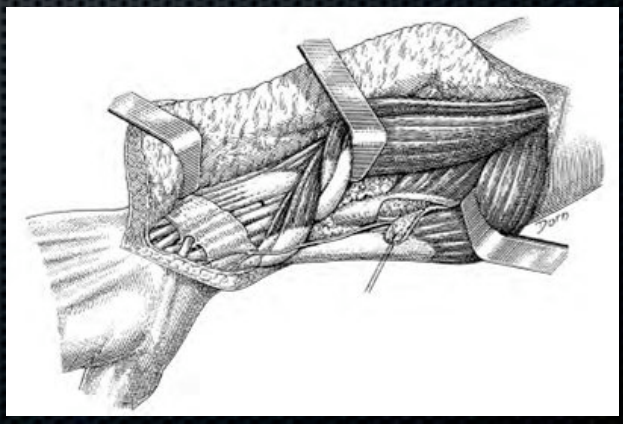
- Wrist extension
- Finger extension
- Thumb extension
- CMC joint stability

Radial nerve palsies are frequent and very disabling. On the other hand, tendon transfers indication and technique have been well defined in that particular lesion. One has to reconstruct three functions: wrist extension, finger extension and thumb extension.

Wrist extension

- Pronator teres to Extensor carpi radialis brevis
  - Need to take a strip of periosteum
  - Should be fixed at the end (to test finger extension using the tenodesis effect)





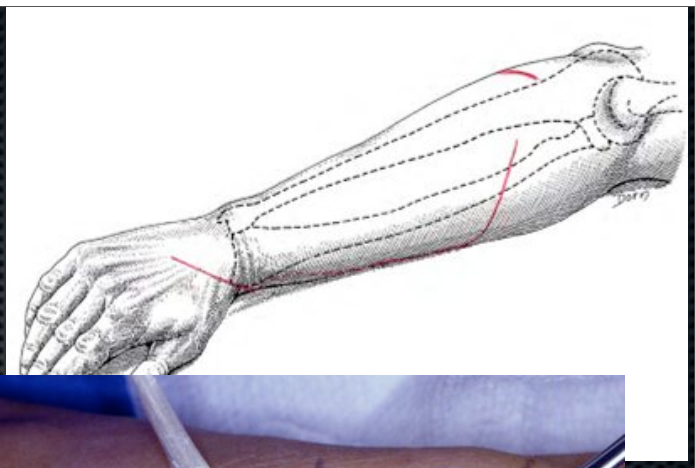
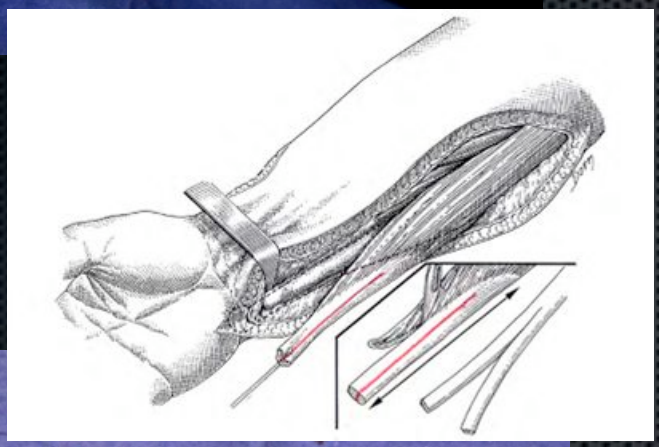
Wrist extension will be restored by using the pronator teres with a strip of periosteum that will be transferred to the ECRB to limit the risk of postop radial inclination. Fixation of this transfer will be done at the end after tensioning of the finger and thumb transfers.

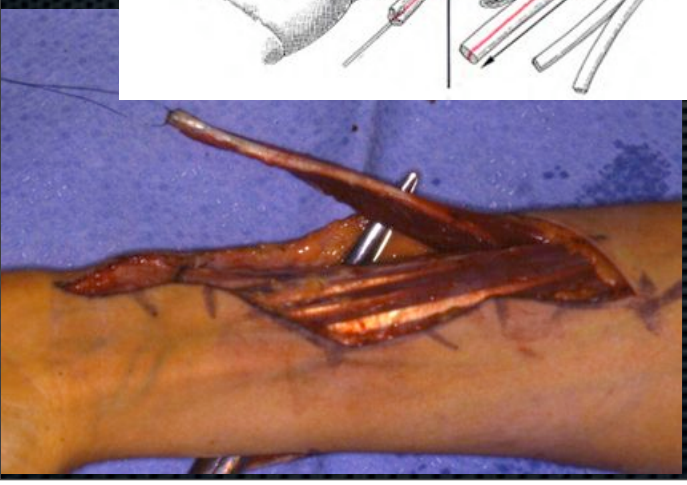
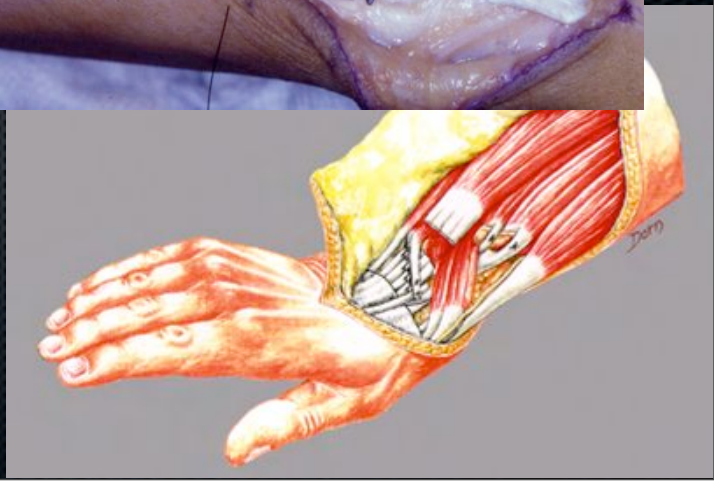
Finger & thumb extension

- FCU around the wrist to EDC, EIP (+/- EPL) & PL to EPL (Tubiana)
- FCR through the IOM to EDC, EIP (Tsuge, Brand)
- FDS 3,4 through IOM to EDC (ring), EIP & EPL (long) (Boyes)

Sutures are made proximal to extensor retinaculum and paralyzed tendons are not divided

For finger extension there is a large debate on whether or not using the FCU or the FCR. Tubiana, my teacher, favored the FCU transfer to limit the potential radial wrist inclination that can be observed postop, particularly with a posterior interosseous nerve palsy, where the innervation to ECRL is preserved.

Large skin incisions are used and the FCU is passed around the wrist to be fixed to the finger extensors

Finger & thumb extension

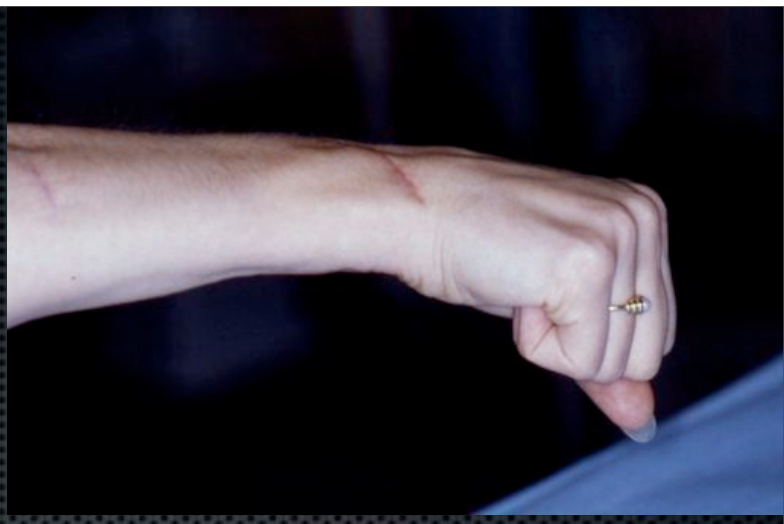
- FCU around the wrist to EDC, EIP (+/- EPL) & PL to EPL (Tubiana)
- FCR through the IOM to EDC, EIP (Tsuge, Brand)
- FDS 3,4 through IOM to EDC (ring), EIP & EPL (long) (Boyes)

Sutures are made proximal to extensor retinaculum and paralyzed tendons are not divided

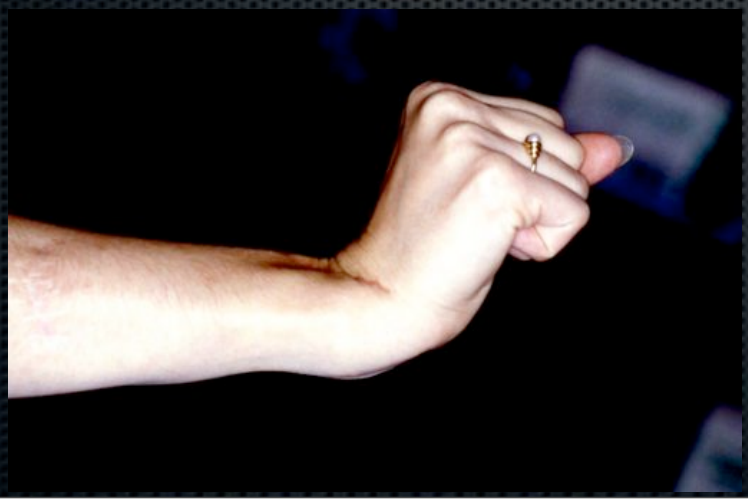
Others like Tsuge in Japan have favored the use of the FCR, to preserve the strength of the FCU which is the strongest wrist flexor.

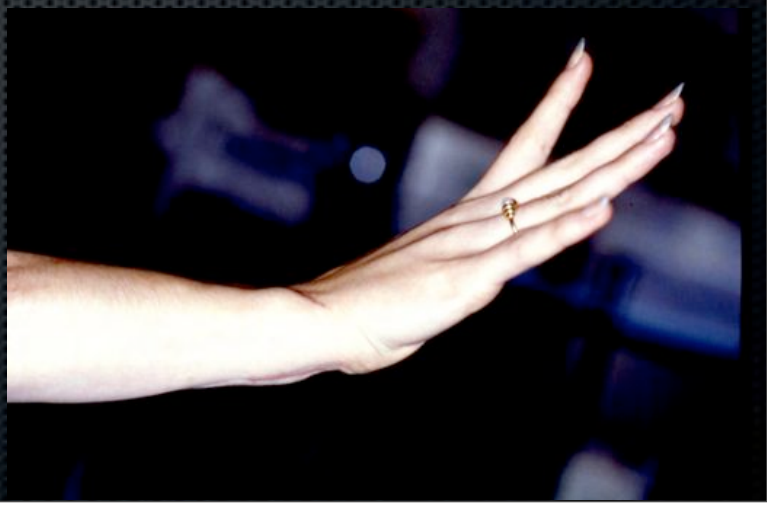
In that situation the transfer is passed directly through the interosseous membrane. In patients with a palmaris longus, the tendon is sutured to the re-routed EPL like in Tubiana's technique.

Results



- Amplitude: wrist flexors 3 cm, Finger extensors 5 cm





Functional results are usually good but one has to remember that wrist flexor and finger extensors do not have the same amplitude. Patients usually have a good wrist extension, a limited wrist flexion and need the tenodesis effect to have a complete finger extension.

Results: Dunnett 1995

- 49 injury to the radial nerve (22) or brachial plexus (27).
- 5.6 years FU. Function improved in 84%
- Impaired coordination and dexterity > 60%
- Premature fatigue > 80%
- Wrist power extension 22% of contralateral side (8% to 80%), power of digital extension was 31% (5% to 130%), and power grip was reduced to 40% (5% to 86%).

I know of one large series with long follow-up. Most patients improved, however fatigue and loss of power were frequent postoperatively
55% of patients had difficulty grasping or releasing large objects.

Median nerve

Median nerve function to restore

- Thumb abduction and opposition (low palsy)
- Thumb flexion (high palsy)
- Flexion of the index and middle fingers (high palsy)
- (Improve sensibility over distribution of the median nerve)

Function to restore after median nerve injury depends of its level. For low-level median nerve injury, thumb opposition is the only motor function to restore.

Pre-requisites before opposition transfer

- Long-standing palsy may lead to first web contracture, supination deformity and joint stiffness that may need surgical release before tendon transfer

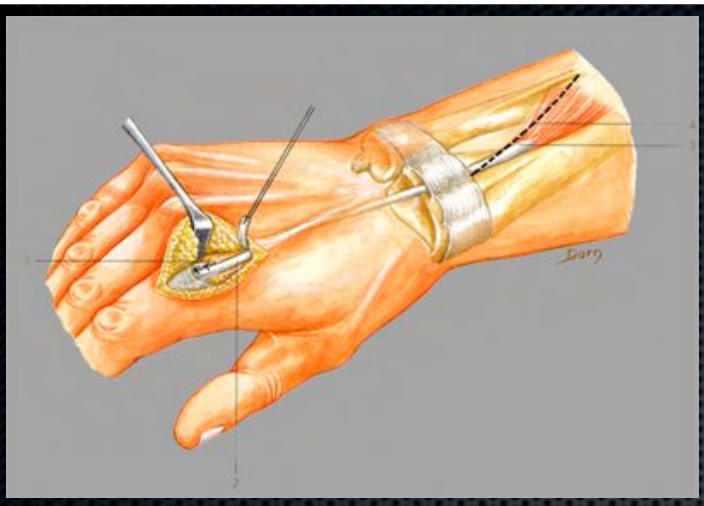
Mobile CMC
Adequate 1st web
Passive opposition
Finger motion
Functioning EPL, FPL, APL
(Thumb and finger sensibility)

As a pre-requisite, the thumb must be mobile and reconstructive transfers will fail if there is contracture of the first web space or joint stiffness

Thumb opposition

- Various techniques and transfers have been described, both passive and active and should be tailored to the patient's need
  - EIP to APB (and EPL) - Aguirre & Caplan
  - FDS (ring) but usually either severed or paralyzed and need more force (43%) to obtain the same function (Anderson 1992)

The EIP is the preferred transfer to achieve abduction of the thumb. It is almost always available and strong enough

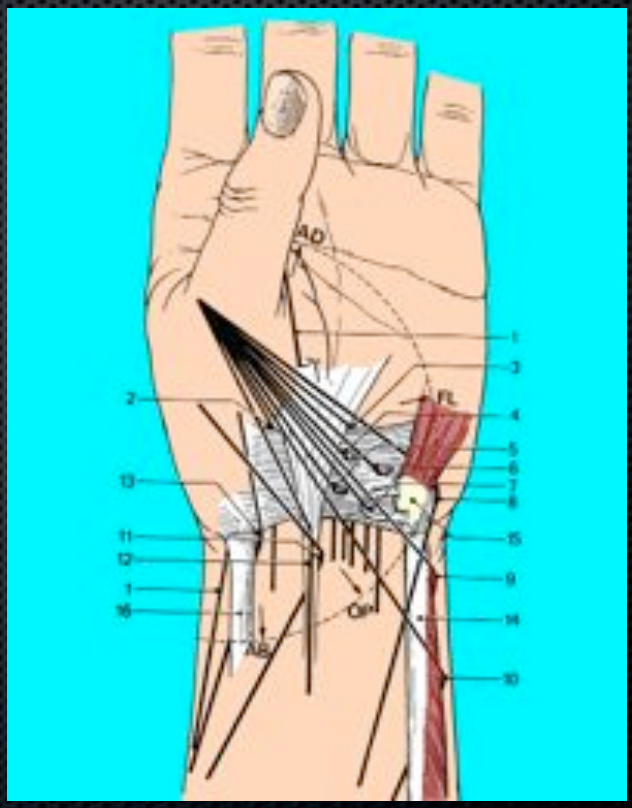


EIP transfer

A small portion of the extensor hood should be taken with the tendon to ensure it will reach its insertion site. An incision at the dorsum of the hand may be needed to free the attachment between the EIP and EDC. The EIP is then freed proximally. A third incision is made over the pisiform.

Thumb opposition

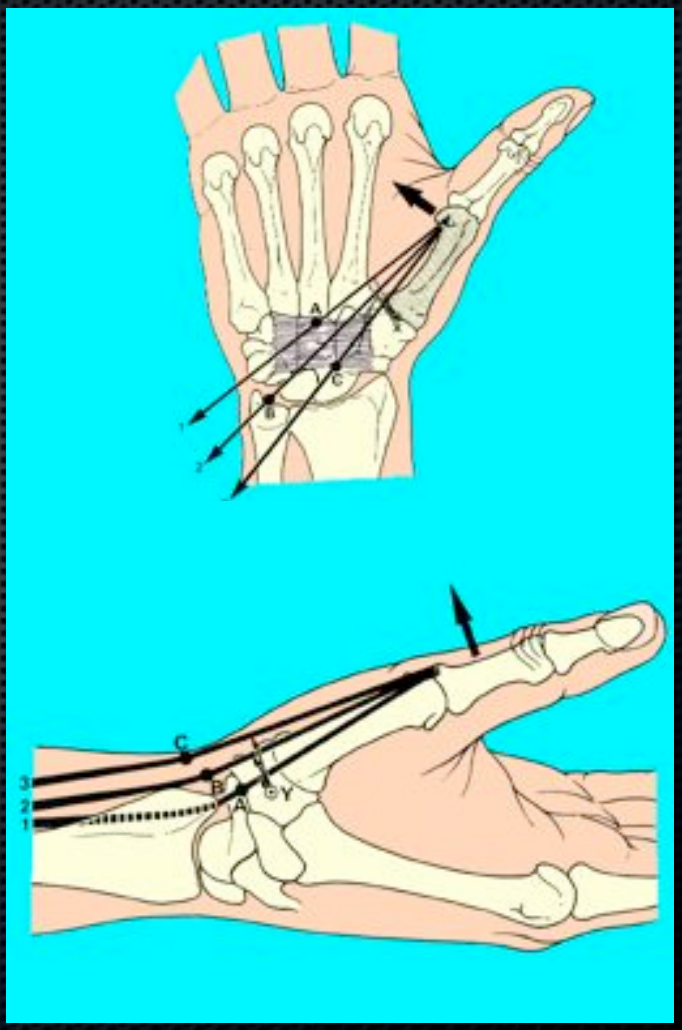
- The motor (EIP / FDS)
- The pulley ?
- The distal fixation ?



The tendon is advanced subcutaneously around the ulnar border of the forearm by using the pisiform and adjacent vertical fibrous tissue as a pulley. However many options are available for the choice of a pulley.

The pulley

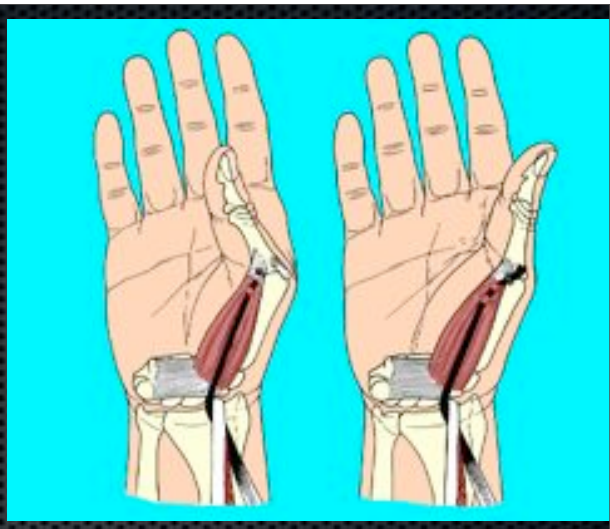
- Adduction is proportional to the length of the moment between tendons and axis of flexion (X)
- Ante-flexion is proportional to the length of the moment between tendon and axis of TM (Y)

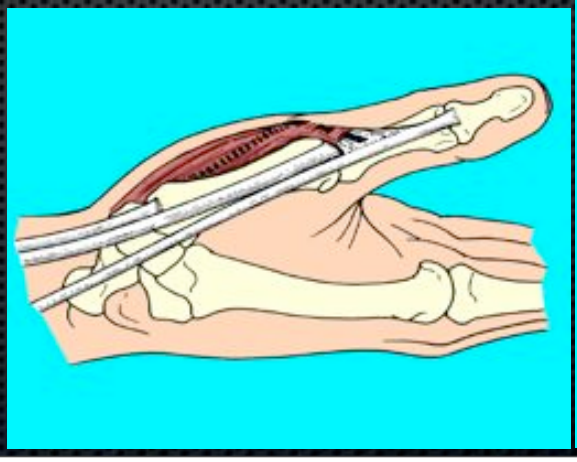


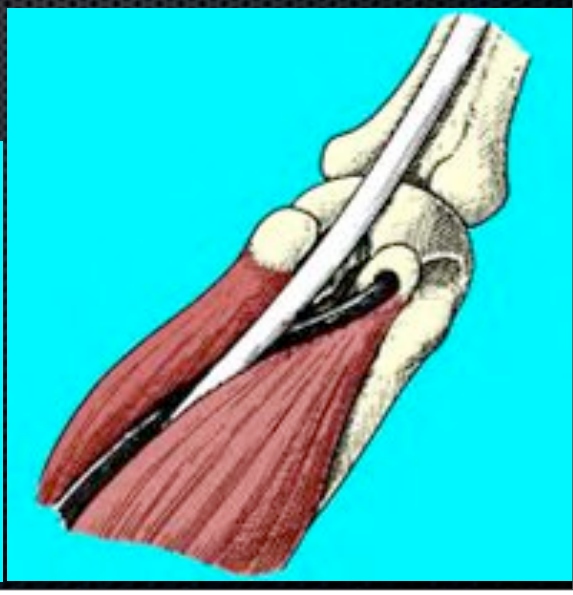
This choice depends of the function to be restored. In pure median nerve injury, ante-flexion will be favored, while in combined median-ulnar nerve palsy some additional adduction is needed.

Distal fixation

- Along the axis of the APB
- Expansion to the dorsum of the axis if extensors are weak (Roach 2001)







A recent study has shown that for distal fixation, the FPB and radial dorsal extensor hood site resulted in statistically highest pinch force. Distal fixation depends also of the other associated nerve lesions.

FDS transfer

- Loss of grip strength
- Loss of PIP extension (8° in 50% of patients North 1980)
- Good to excellent results in 60-85% of patients (Bohr 1953, Jensen 1978, Anderson 1992)

A FDS transfer is the other option and good results have also been reported

Results

- Anderson 1992 (166 pts)
- 89% good to excellent after EIP, 85% after FDS
- EIP > FDS in their series
  - FDS (ring) needs more force (43%) to obtain the same function

However in Anderson's series, results were slightly inferior to EIP transfer as an average.

Ulnar nerve

TABLE 4

Isolated Ulnar Palsy

Needed Function	Preferred Motor	Alternate Transfer
Thumb adduction for key pinch (low palsy)	ECRB, with free tendon graft between third–fourth metacarpals, to tendon of APB	FDS (middle) to abductor tubercle of thumb, with palmar fascia as pully
Thumb-index tip pinch	Slip of APL to first dorsal interosseous tendon, and arthrodesis MCP joint of thumb	EPB to first dorsal interosseous tendon, if MCP joint of thumb arthrodesed
Proximal phalanx power flexion and integration of MCP and IP motion (clawed fingers)	ECRL with 2- or 4-tailed graft passed volar to deep transverse metacarpal ligament to either A2 pulley of flexor sheath or to radial band of the dorsal apparatus	If wrist flexion contracture, FCR with 4-tailed graft to either flexor sheath (A2 pulley) or lateral bands of dorsal apparatus
Metacarpal (palmar) transverse arch and adduction for small finger	EDM tendon is split and ulnar half is transferred volar to deep transverse metacarpal ligament to radial collateral ligament of proximal phalanx or A2 pulley of the flexor sheath (EDC of small finger must be effective)	If small finger is clawed as well as abducted, insert ulnar half of EDM only into A2 pulley
Volar sensibility for ring and small fingers	Proximal median digital nerve translocated to distal ulnar digital nerve	Free or vascularized nerve graft
Distal finger flexion—for ring and small fingers (high palsy)	FDP (middle) tenodesed to FDP (ring and small), with possible tendesis of distal IP joints in the ring and small fingers	
Wrist flexion—ulnar side	FCR to insertion of FCU	PL to insertion of FCU

From Omer 2004

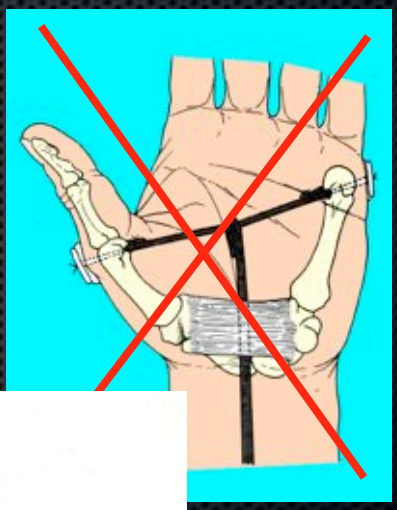
Ulnar nerve palsy results in a hand with so many functional problems that there is no accepted program for reconstruction. Here is a lists of possibilities

Function to restore after low ulnar nerve palsy

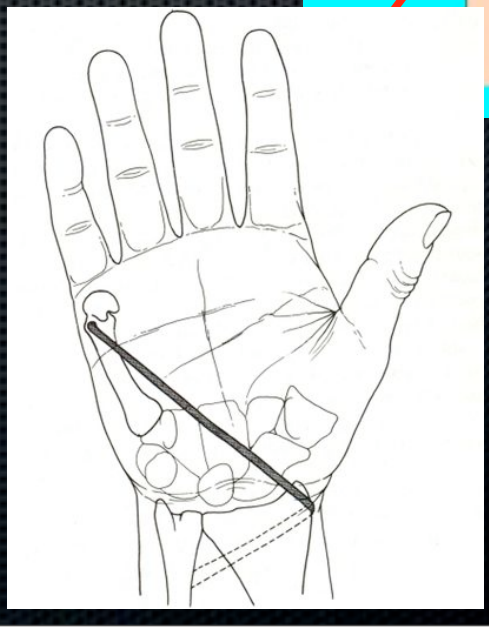
- Loss of hypothenar muscles
  - Wartenberg's sign
  - Loss of transverse metacarpal arch

On the ulnar side, patients usually complained of a flat hand with loss of opposition and a permanent abducted little finger

Loss of carpal arch

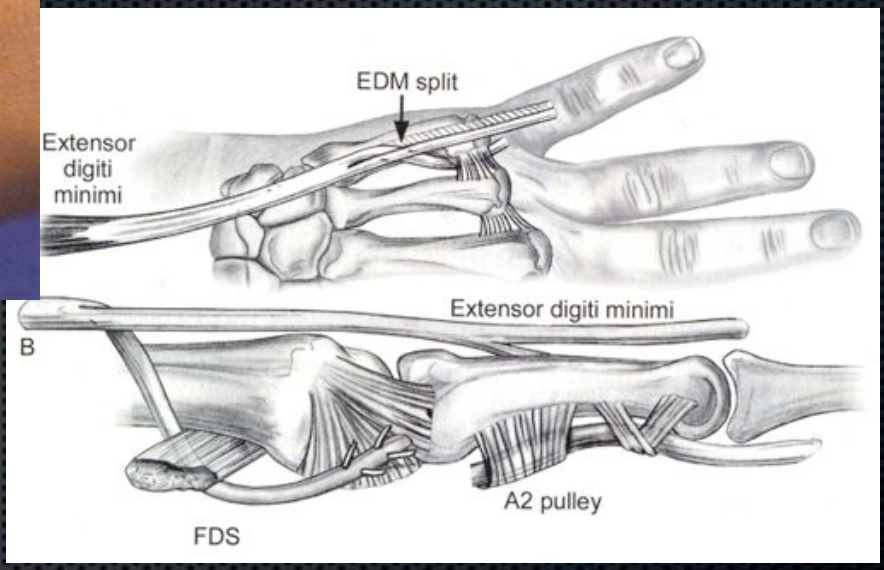


- Bunnell's technique have been abandoned
- Ranney's transfer (EDQ) is sometimes performed



Loss of ulnar opposition are sometimes corrected using an EDQ transfer to the neck of the fifth metacarpal

Correction of Wartenberg's



- Transfer of the ulnar slip of the EDM to the radial side
- In case of clawing, the radial slip is transferred volarly

Correction of permanent abduction of the littler finger can be done either by transferring radially the ulnar slip of the extensor digiti quinti or, in case of clawing

by transferring it volar to the intermetacarpal ligament to correct the MCP hyperextension.

Function to restore after low ulnar nerve palsy

- Loss of interosseous muscle (+ lumbricales)
  - Claw hand
  - Loss of key pinch (10% nl)
  - Loss of normal finger flexion
  - Loss of strength (70-80% loss)

Paralysis of the intrinsics leaves the hand with a severe deficit, including loss of grip strength.

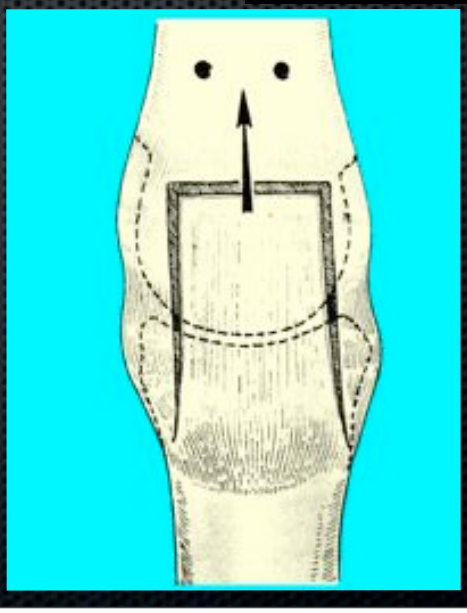
Claw hand correction

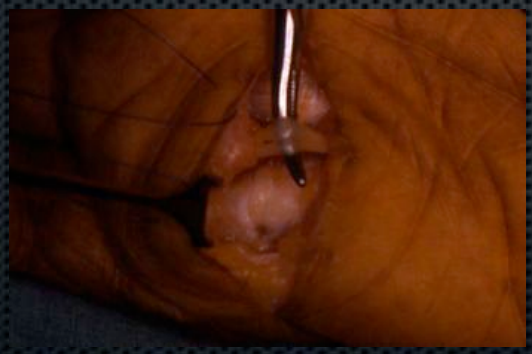
- Static procedures (capsulodesis and static tenodesis, rarely bone block)
- Dynamic procedures
  - Dynamic tenodesis (Fowler)
  - Tendon transfer

For the claw hand many techniques have been proposed either static, or dynamic using either tenodesis or a tendon transfer

Capsulodesis

- Stretch with time whatever the technical variations used in lax patients

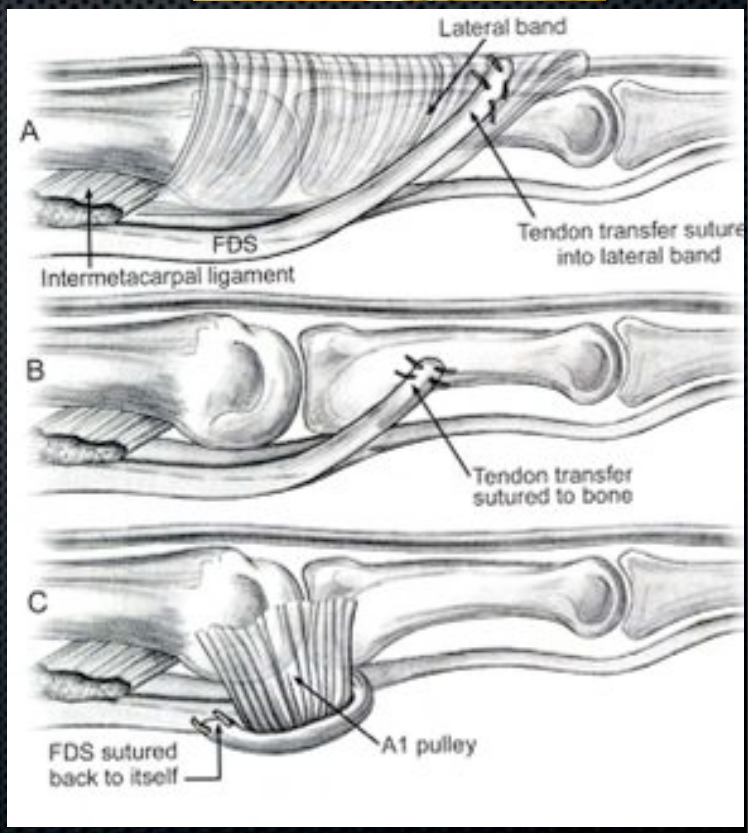




Capsulodesis is the most well known static procedure. It avoids MCP hyperextension, but usually they stretch with time especially in lax patients.

FDS transfer

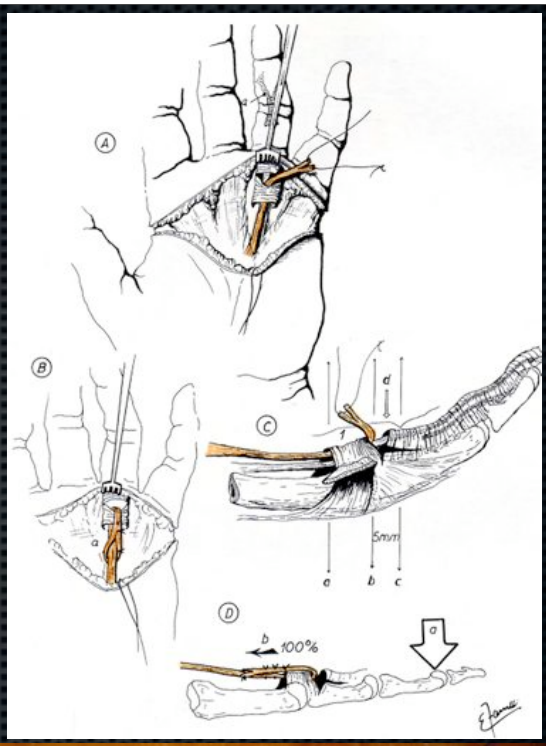
- Lasso
  - Patients will loose 20% of their grip strength
- Bone (Burkhalter)
- Stiles-Bunnell (if Bouvier's maneuver does not correct hyperextension)

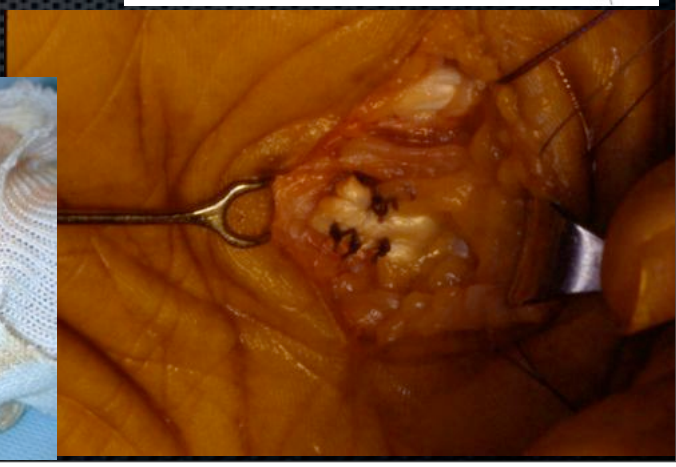


This is why tendon transfer is usually preferred. When using a FDS transfer, in patient's with a positive Bouvier's sign, bone fixation or the lasso procedure are adequate. If the patient is unable to obtain a full extension of the PIP joint, then distal fixation to the lateral bands according to Stiles and Bunnell would be more adequate.

Drawbacks

- Brandsma (1992) observed 15% swan-neck deformity, 29% DIP flexion contracture and 26% PIP flexion contracture over 158 FDS transfers
- North (1980) observed no complications





There are some reports of frequent sequelae with the use of the FDS transfer, even in large series. However others do not report such complications.

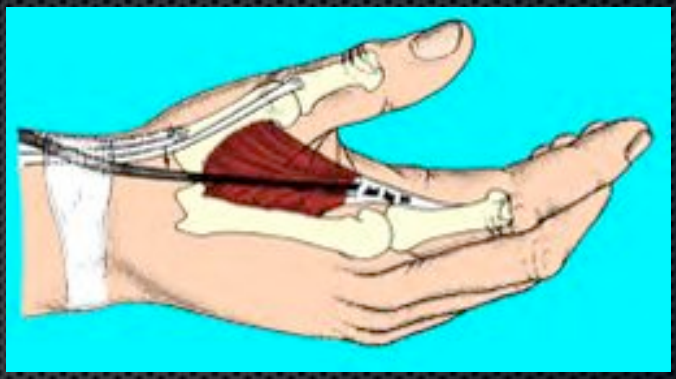
Results

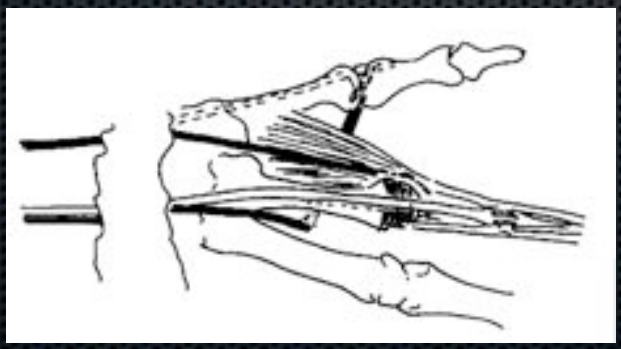
- Ozkan 2003 (44 patients)
- Lasso and ECRL-4 tail most effective for grip strength
- FDS 4-tail most successful in correcting the claw hand deformity, especially in long-standing paralysis in which there was elongation of the extensor apparatus.

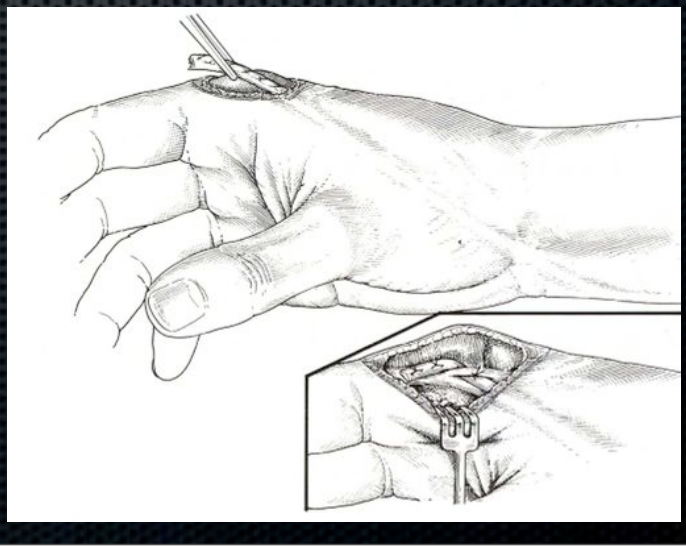
I know of one paper comparing different techniques for correction of claw hand deformities in patients with median and ulnar nerve injuries. Ozkan et al. reported little differences with the Lasso, the FDS 4-tail and the ECRL 4-tail techniques

1st interosseous restoration

- APL accessory slip (+ graft) (Neviaser 1980)
- PL (+ graft) (Hurayama 1986)
- EPB (Bruner 1948)







On the radial side, most patients stabilize their index with their long finger. However pinch may be weak and tendon transfer may help to restore a key pinch. Many techniques have been designed however strength is only improved by 10 to 15% according to a review by Hastings.

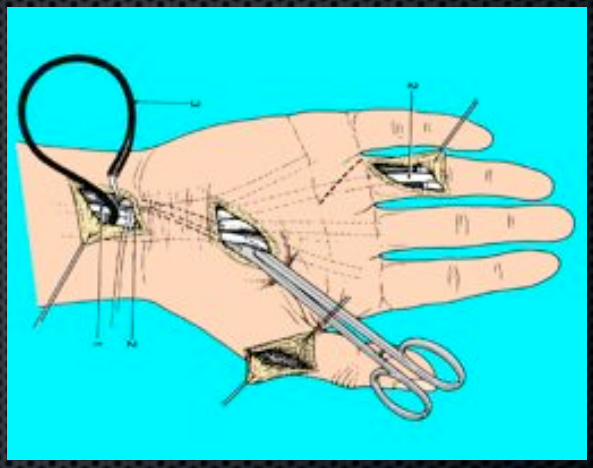
Function to restore after low ulnar nerve palsy

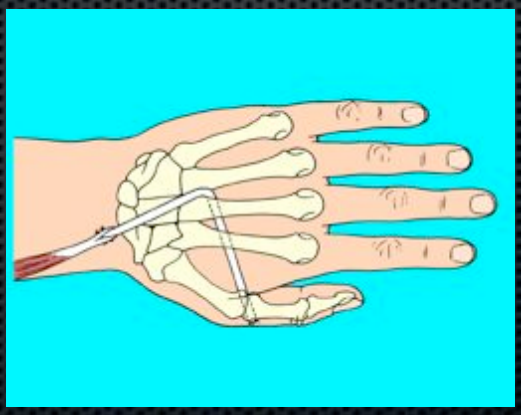
- Loss of Thenar muscles
  - Jeanne's and Froment's signs
  - Loss of key pinch

At the thumb, the MCP joint must be stabilized before adduction and or opposition are restored. An arthrodesis may be needed at the MCP.

Thumb adduction

- FDS (ring) to ulnar side of the thumb
- EIP (or ECRB + graft) through the metacarpals





We have already see the principles for thumb opposition reconstruction. If one has only adduction to reconstruct, the donor tendon are similar in low-level palsy but the path and distal fixation are different.

Results

- Fischer 2003, 9 patients, ECRL to AP, APL to 1st DIO
- Key pinch 73%, pulp-to-pulp pinch 72%, power grip 73%
- Force of thumb adduction 63%
- Force of index finger abduction 58%
  - Large variations between patients

Clinical results are scarcely reported in the literature. There is always some improvement but not a normal hand.

Combined lesions

TABLE 6

Combined High (Proximal) Median and Ulnar Palsy

Needed Function	Preferred Motor	Alternate Transfer
Thumb adduction (AP)—key pinch	ECRB with free tendon graft between third and fourth metacarpals to APB tendon	BR or EIP with free tendon graft between third and fourth metacarpals to abductor tubercle of thumb (APB tendon)
Thumb flexion (IP joint)	BR to FPL in forearm	Tenodesis of FPL distal to MCP joint of thumb
Thumb abduction (APB)	EIP with pisiform pulley to insertion APB tendon (plus) EPL tendon	EPL or ECU with free graft around pisiform pulley to APB tendon (thumb MCP is arthrodesed and no active motion at thumb IP joint)
Thumb—index tip pinch	Thumb MCP joint arthrodesis; and APL slip with free tendon graft to first dorsal interosseous tendon	EPB or PL to first dorsal interosseous, and fusion of thumb MCP joint
Finger flexion (FDP)	ECRL to all 4 tendons of FDP with possible tenodesis of distal IP of ulnar 3 fingers	Biceps brachii extended with FCR tendon to tendons of FDP
Power for flexion of proximal phalanx with integration of MCP and IP motion (clawed fingers)	Tenodesis of all 4 digits with free tendon graft from dorsal carpal ligament volar to deep transverse metacarpal ligament to lateral bands of extensor apparatus (or) from deep transverse metacarpal ligament to extensor apparatus	Capsulodesis of MCP volar capsule (or) arthrodesis of PIP joints (or) arthrodesis of MCP joints
Metacarpal (palmar) arch and adduction for small finger	EDM to deep transverse metacarpal ligament (EDC of small finger must be active)	EDM to radial lateral bands (extensor hood) of the ring and small finger
Wrist flexion	—	ECU to insertion of FCU
Median and ulnar volar sensibility	Superficial radial innervated index fillet flap to palm (or) first dorsal metacarpal artery neurovascular island pedicle flap	Superficial radial nerve translocation (or) free vascularized nerve graft

Combined median and ulnar nerve palsies are the most frequent. The complete loss of palmar sensibility and intrinsic motor muscles produces an almost useless and often clawed hand. Reconstruction of the thumb is very important.

But there are other associated lesions and the more complex the injury, the more difficult the reconstruction

Conclusions

- Nerve repair is the best technique available even if results are still disappointing
- Sensory deficit is a major complication which reconstruction is difficult with limited results
- Tendon transfer are well described for complete paralytic hand
- Indications are less described for patients with partial recovery

This overview of all the possible techniques available for functional reconstruction of the hand after a nerve lesion must not hide the reality:
- Results of nerve repair are usually limited but nerve repair if possible is by far the best technique
- Sensory deficit is very disabling for patients and to date our techniques give only limited and somewhat frustrating results.
- Tendon transfer are well defined but their description date back to the 50s. They are useful for completely paralyzed patients but they may not be useful for patients with some recovery. With the improvement of nerve repair there is a new area for tendon transfer surgery
- But moreover, it is from the neurological research, the use of new biologic treatment that we will improve our results at the end

Arigatou Godzaimas

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