Update on Tendon Transfers for Peripheral Nerve Injuries

Joshua A. Ratner, MD, Allan Peljovich, MD, Scott H. Kozin, MD

Tendon transfer surgery to restore fundamental wrist and hand function is made possible by the redundancy that exists among the actions of our upper-extremity musculature. Potential donors for transfer are those muscles with adequate power to motor the recipient tendon, similar tendon excursion to the recipient, and function in phase with the recipient. Resolution of wound healing, union of fractures, and mobilization of stiff joints are prerequisites for a functioning tendon transfer. Injuries to the radial, median, and ulnar nerves occur above (high nerve injury) and below the elbow (low nerve injury). High and low nerve injuries result in different functional deficits that require unique tendon transfers to enhance function. This report discusses the various tendon transfers necessary to overcome deficits resulting from high and low radial, median, and nerve injuries. (J Hand Surg 2010;35A:1371–1381. © 2010 Published by Elsevier Inc. on behalf of the American Society for Surgery of the Hand.)

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FUNCTIONAL DEFICITS RESULTING from peripheral nerve injuries vary with the particular nerve involved, the location of the lesion, and the extent of concomitant injuries to bone and soft tissue structures. Tendon transfer surgery to restore fundamental wrist and hand function is made possible by the redundancy that exists among the actions of our upper-extremity musculature. The development of a surgical plan for tendon transfers involves identifying those muscles that are denervated, evaluating the patient’s functional deficits, and considering which muscles are available for transfer. Potential donors for transfer are muscles with adequate power to motor the recipient tendon, similar tendon excursion to the recipient, and those with function in phase with the recipient (ie, wrist extension and finger flexion, thumb adduction and wrist flexion, finger extension and thumb abduction). Certainly, existing function should not be sacrificed by the harvest of an essential muscle-tendon unit.

Timing of surgery depends on the achievement of tissue equilibrium. Resolution of wound healing, union of fractures, and mobilization of stiff joints are prerequisites for a functioning tendon transfer. Clinical success requires a multidisciplinary approach to patient care including contributions by physicians, nurses, therapists, and electrodiagnosticians.

RADIAL NERVE

Physical examination

The most proximal muscle innervated by the radial nerve is the triceps, and in most cases of a peripheral nerve injury, its function as an elbow extensor is preserved. A radial nerve lesion proximal to the elbow results in loss of function of all of the wrist extensors (extensor carpi radialis longus [ECRL], extensor carpi radialis brevis [ECRB], and extensor carpi ulnaris), yielding a wrist drop (Fig. 1). Loss of wrist extension results in the inability to generate power grip, which can easily be tested using a dynamometer. Extensor digitorum communis (EDC) function is tested by asking the patient to simultaneously extend the metacarpophalangeal (MCP) joints of the index through small digits. Extensor indicis proprius (EIP) and extensor digitii minimi function is evaluated by asking the patient to
extend the index and small finger MCP joints in isolation. Extensor pollicis brevis and extensor pollicis longus (EPL) function is assessed by asking the patient to extend the thumb MCP and interphalangeal (IP) joints, respectively.

In contrast to a high radial nerve palsy (palsy of the radial nerve proper), a lesion distal to the elbow will involve only those muscles innervated by the posterior interosseous nerve. Clinically, examination of the patient with low radial nerve palsy demonstrates wrist radial deviation during active extension because of maintenance of ECRL function and loss of extensor carpi ulnaris function.

After initial evaluation and diagnosis of radial nerve palsy, it is recommended that the patient be fitted for a radial nerve splint. Traditional outrigger splints or newer lower-profile splints prevent the development of wrist and MCP joint contractures and can considerably enhance function (Fig. 2). During subsequent visits, serial physical examinations of a patient with a radial nerve palsy are an important tool for monitoring recovery, guiding treatment, and managing patient expectations.

Despite the limited functional consequence of a loss of brachioradialis (BR) function after a radial nerve injury, evaluation of this muscle for signs of reinnervation is extremely important in the weeks and months after injury. Because the BR is the first muscle innervated by the radial nerve in the anterior compartment of the arm, reinnervation of the BR implies nerve conduction distal to the site of the lesion. Once motor function of the brachioradialis is restored, it is likely that wrist and MCP joint extension will soon follow.

**Timing**

The preferred timing of tendon transfers for a radial nerve palsy falls into one of 2 categories: early transfers done to act as an internal splint or later transfers to restore function when recovery is deemed unlikely. Early transfers are performed within weeks of nerve injury and usually consist of a single tendon transfer for wrist extension. This transfer for wrist extension allows power grip by placing the finger and thumb flexors at a biomechanical advantage. Release of finger opening is accomplished by wrist flexion and the associated tenodesis effect of the long finger extensor tendons. The preferred timing of delaying transfers varies widely among authors, with intervals ranging between 6 and 18 months.

The expected time to recovery of any peripheral nerve lesion can be calculated based on the work of Seddon. Neurapraxias tend to recover within 3 to 4 weeks from injury, as remyelination occurs promptly. In contrast, an axonotmesis injury involves Wallerian degeneration and implies incomplete and slow regeneration. Assuming a rate of nerve regrowth of one mm/day, the expected time to clinically detect return of function can be estimated based on the distance between the nerve lesion and the site of innervation to the BR. Therefore, it is reasonable to expect that in a radial nerve lesion occurring at the midshaft of the humerus, it would take at least 6 months to detect recovery. Delaying tendon transfers until that time seems reasonable to allow sufficient time for nerve recovery. During this time, a radial nerve splint will enhance function and should be prescribed.

**Radial nerve tendon transfers**

In an isolated high radial nerve injury, muscle-tendon units innervated by the median and ulnar nerve are possible donors. Given the preserved function of both the wrist flexors (ie, flexor carpi radialis [FCR] and flexor carpi ulnaris [FCU]) and both pronators (pronator teres [PT] and pronator quadratus), there are several available options. Classic transfers for radial nerve palsy include the Brand, Jones, and modified Boyes.4,5
transfers. Among these transfers is the common use of
the PT to ECRB and the palmaris longus (PL) to EPL.
The preferred choice of a motor to reanimate the EDC
varies with each author. In a low radial nerve palsy, a
transfer for wrist extension is not required because
ECRL function is preserved.

Although the authors have used each of the 3 sets of
transfers, the preferred transfers for radial nerve palsy
are the PT to ECRB, PL to the rerouted EPL, and FCR
to EDC. The rationale for this last choice is the preser-
vation of the FCU, which is an important contributor to
power tasks such as hammering. Preservation of this
ulnar-sided flexor also helps to balance the radial devi-
ation caused by the tendon transfers to the ECRB. This
is particularly important in the case of low radial nerve
palsy with an intact ECRL. Harvest of the FCU is also
more time-consuming compared with the FCR. The
FCU has muscle and fascial attachments along the
entire ulna that must be freed to maximize its excursion.
If the FCR is chosen for the EDC motor, a single
utilitarian curvilinear radial-sided incision can be used
to perform all of the transfers.

In our experience, transfer of the flexor digitorum
superficialis (FDS) either through the interosseous
membrane or around the ulnar border of the forearm to
the EDC is more prone to fail. Difficulties with reha-
bilitation to activate this out-of-phase transfer (ie, learn-
ing to fire a finger flexor as an extensor) and the devel-
opment of adhesions after interosseous transfer are
common. In contrast, transfer of the FDS to the wrist
extensors is an in-phase transfer and a good alternative
to PT transfer.

**Surgical technique in brief**

The FCR and PL are readily accessible beneath the
full-thickness volar forearm flap. Branches of the radial
sensory nerve and the radial artery are identified and
protected. Dorsal dissection allows exposure of the PT
tendon, located beneath the BR musculotendinous junc-
tion and deep to the emerging radial sensory nerve.7
The PT tendon is harvested with a strip of periosteum to
augment its coaptation to the ECRB tendon. Further
elevation of the dorsal skin flap exposes the ECRB,
EPL, and EDC within the index, long, and ring finger
dorsal compartments, respectively. The PL is released
from its insertion into the palmar fascia and mobilized
toward the freed EPL tendon. The EPL must be trans-
posed from the third compartment toward the PL. This
transposition provides better thumb extension and elim-
inates the thumb adduction vector of the EPL.

Tendon transfers of the thumb and finger extensors
are performed before transfers about the wrist. This
sequence allows the surgeon to judge sufficient tension
using wrist motion. The EPL tendon is woven into the
PL and the FCR is woven into the EDC using a tendon
braider (Fig. 3). Tension is adjusted until wrist flexion
of 30° produces adequate thumb and finger extension
via tenodesis and wrist extension allows passive finger
flexion into the palm. Once digital extension transfers
are completed, the PT is woven into the ECRB (Fig. 4).
Tension is adjusted until a 30° extension resting posture
of the wrist is achieved. All Pulvertaft tendon passes are
secured with braided nonabsorbable suture. Once skin
flaps are closed, the extremity is splinted with the wrist
in 30° of extension, the MCP joints in full extension,
and the thumb abducted with the IP joint in extension.

**MEDIAN NERVE**

**Physical examination**

Presentation of the patient with a median nerve injury
varies with the level of the lesion. High median nerve
injury results in a loss of flexor pollicis longus (FPL) IP
joint flexion, flexor digitorum profundus (FDP) index
and long function, pronation of the forearm, and loss of
thumb opposition (Fig. 5). Simple examination findings include the inability to make an “OK” sign, which requires thumb IP and index distal IP (DIP) joint flexion. Loss of sensation in the median innervated digits is also present. Low median nerve injury primarily affects thumb opposition and sensibility. The physical examination must test for palmar abduction to isolate abductor pollicis brevis function (Fig. 6). Thumb opposition must be carefully assessed and compared with the uninjured side (Fig. 7). Opposition is a combination of palmar abduction, MCP joint flexion, and pronation. After a median nerve injury, MCP joint flexion is preserved via function of the flexor pollicis brevis, which is dually innervated by the median and ulnar nerves. However, true opposition is not possible because palmar abduction and pronation are absent.

Owing to the proximity of the median nerve to the ulnar nerve and brachial artery in the arm, a high median nerve lesion warrants a detailed assessment of ulnar nerve function and hand vascularity.

**Timing**

Tendon transfers for median nerve injuries are performed when recovery, whether spontaneous or after nerve repair, is no longer expected. Prerequisites for successful transfers that were previously mentioned should be met, especially tissue equilibrium.

**Tendon transfers for low median nerve palsy: thumb opposition transfers (opponensplasties)**

The loss of thumb opposition results in a considerable impairment of hand function. Bunnell described an opponensplasty that passed a tendon through a constructed pulley at the level of the pisiform, across the palm and to the dorsal ulnar aspect of the thumb metacarpal. This technique provided superior opposition, a motion inclusive of palmar abduction, flexion, and pronation of the thumb. A recent biomechanical study investigated pulley location and insertion sites for transfer insertions and concluded that the pulley described by Thompson and the Guyon’s canal pulley exerted the least friction force. Insertion points of opposition transfers were also examined with a more palmar and radial insertion allowing better opposition (pulp-to-pulp contact between thumb and fingers).

Numerous variations of the originally described technique have been used to restore opposition of the thumb, using various muscles innervated by the ulnar or radial nerve. Donor muscle-tendon units have included the FDS of the long or ring finger (not available in high median nerve palsy), EIP, EPL, extensor carpi ulnaris, ECRL, extensor digiti minimi, PL, and abductor digiti quinti.

Our preferred technique for restoration of opposition in isolated low median nerve palsy is the ring finger FDS opponensplasty.

**Surgical technique in brief:** An oblique standard incision is made over the ring finger A1 pulley. The pulley is incised longitudinally, and the FDS tendon is isolated and separated from the FDP tendon (Fig. 8). The ring finger is flexed, and the FDS tendon is divided transversely just proximal to its bifurcation. The tails of the FDS tendon are left behind to adhere to the floor of the tendon sheath and prevent proximal interphalangeal (PIP) joint hyperextension.

At this point, a pulley for the ring finger FDS tendon
is constructed. An oblique incision is made at the volar ulnar distal forearm in the region of the FCU tendon insertion into the pisiform. The FCU and the ring finger FDS tendons are exposed, and the ulnar neurovascular structures are protected. The radial half of the FCU tendon is divided transversely approximately 4 cm proximal to its insertion on the pisiform (Fig. 9). The radial half of the tendon is separated longitudinally from the ulnar half, creating a distally based strip of tendon graft. The tendon graft is looped distally and passed through the distal portion of the FCU near the pisiform insertion and secured with nonabsorbable sutures. The ring finger FDS tendon is pulled through the carpal tunnel into the proximal wound. The ring finger FDS tendon is passed through FCU loop (Fig. 10). A subcutaneous tunnel is created between the pisiform and a radial incision along the thumb MCP joint. The donor tendon is routed through the pulley and into the radial thumb incision (Fig. 11).

Several options for attachment of the tendon transfer have been described with more dorsal insertions enhancing pronation and more radial attachments yielding


FIGURE 8: Identification of the ring finger FDS tendon (courtesy of Shriners Hospital for Children, Philadelphia).

FIGURE 9: One half of the FCU tendon looped distally to create a pulley (courtesy of Shriners Hospital for Children, Philadelphia).
greater abduction.\textsuperscript{13,14} The exact position for insertion depends on the needs of the patient, determined before surgery (Fig. 12).

Regardless of the chosen insertion site, correct tensioning is imperative to achieve an optimal result. Tensioning is set using tenodesis, such that maximal thumb opposition is present with passive wrist extension and adequate thumb extension is noted with passive wrist flexion. After skin closure, the thumb is immobilized in opposition and the wrist in slight flexion to remove any tension from the tendon transfer.

Additional transfers for high median nerve palsy
In addition to restoration of thumb opposition, high median nerve palsy requires reanimation of the FPL and FDP (index and long) tendons. The BR is the preferred donor for thumb IP flexion and is transferred to the FPL tendon (Fig. 13). Index and long finger IP flexion is restored by transferring the long and index finger FDP tendons to the ring and small FDP tendons, which are innervated by the ulnar nerve. Loss of pronation can be overcome by rerouting the biceps around the radius, which converts the biceps from a supinator into a pronator (Fig. 14).

ULNAR NERVE
Physical examination
The most notable physical finding in low ulnar nerve palsy is the claw posture of the ring and small fingers, owing to intrinsic paralysis (Fig. 15). The index and long fingers do not claw because their lumbrical function is preserved via median nerve innervation. Accord-
ingly, clawing of all digits represents an insult to both
the median and the ulnar nerves. Abduction of the small
finger owing to loss of the palmar interossei providing
adduction force and the unopposed abduction moment
of the extensor digitii minimi (radial nerve innervation)
may be seen (Wartenberg’s sign) (Fig. 16). Froment’s
sign is the recruitment of the FPL during lateral pinch,
resulting in thumb IP flexion owing to loss of the
powerful adductor pollicis (Fig. 17). Loss of intrinsic
function and coordination will lead to the inability to
cross the fingers (Fig. 18). Loss of intrinsic function in
the hand also results in the inability to coordinate MCP
joint flexion with IP flexion and results in roll-up flex-
ion (Fig. 19). This hampers encircling larger objects and
object acquisition. Sensory loss over the small finger
and ulnar border of the ring finger is also found. High
ulnar nerve palsy includes the loss of the FCU and the
FDP to the ring and small fingers. Because of the

**FIGURE 14:** Technique for biceps rerouting (courtesy of Shriners Hospital for Children, Philadelphia). A Skin incision for biceps rerouting. B Isolation of the biceps tendon and lacertus fibrosis. Lateral antebrachial cutaneous nerve just lateral to tendon. C Biceps tendon traced to its insertion into radial tuberosity. D z-Plasty of the biceps tendon is planned along its entire length to ensure sufficient tendon length for passage around the radius. E z-Plasty of entire biceps tendon with long proximal and distal limbs. F A curved clamp (Castameda pediatric clamp; Pilling Surgical, NC) facilitates tendon rerouting around the radius. G Tendon passed through interosseous space and around radius. H Distal limb repaired back to proximal limb using a tendon weave augmented with nonabsorbable suture.

**FIGURE 15:** Low ulnar palsy results in clawing of the ring and small digits (courtesy of Shriners Hospital for Children, Philadelphia).

**FIGURE 16:** Wartenberg’s sign owing to unopposed abduction force of the extensor digitii minimi (courtesy of Shriners Hospital for Children, Philadelphia).
resultant loss of ring and small finger IP joint flexion, true clawing is not seen.

Timing

Tendon transfers for ulnar nerve injuries are performed when recovery, whether spontaneous or after nerve repair surgery, is no longer expected. Similar prerequisites described for successful tendon transfer with radial and median palsies must be present. In the interim, hand therapy to preserve passive range of motion is paramount. In addition, fabrication of a lumbrical bar splint that prevents MCP joint hyperextension will improve function and prevent volar plate attenuation of the ring and small MCP joints. Failure to prescribe this splint will result in an MCP joint extension contracture and reciprocal attenuation of the central slip, which substantially complicates reconstruction.

Low ulnar nerve tendon transfers

The goals of tendon transfers for ulnar nerve palsy include restoration of thumb adduction and index abduction for key pinch, as well as restoration of intrinsic function with MCP joint flexion (with IP extension when necessary).

Tendon transfers for intrinsic function (intrinsicplasty)

Several techniques to improve intrinsic minus hand function are available that employ extrinsic muscles of the wrist and fingers as donor tendons. Two of the more commonly performed surgeries include transfer of a wrist motor with tendon graft extensions (4-tail graft)\(^\text{15}\) and transfer of the FDS (Stiles–Bunnell transfer).\(^\text{16}\) Both procedures rebalance the hand and improve asynchronous finger motion and clawing.

In preparing for tendon transfer surgery for ulnar nerve palsy, a decision must be made regarding the need to include IP joint extension as part of the reconstructive strategy. Bouvier’s test provides valuable in-
formation concerning the necessity of restoring IP joint extension. The test is performed by blocking extension of the MCP joints and asking the patient to extend the IP joints. The ability to extend the IP joints with the MCP joints flexed uses the extrinsic extensors and is deemed a positive Bouvier’s test. In this scenario, the primary goal of the transfer is to provide MCP joint flexion with the insertion of the transfer into the proximal phalanx. A negative Bouvier’s test indicates that the extrinsic extensors cannot extend the IP joints and adding IP extension function with the transfer is necessary. This requires transfer into the lateral bands of the extensor apparatus.

**FDS transfer:** This procedure uses FDS as the donor motor-tendon unit, with the goal of rebalancing the hand, correcting claw deformities, and improving synchronous motion. No increase in strength is anticipated. The FDS from either the index or middle finger is released and split. The 2 tendon tails or slips are transferred through the lumbrical canals of the ring and small fingers and inserted most commonly into the lateral bands of the finger extensor mechanisms. The tendon slips are usually of adequate length and rarely require tendon graft extensions when harvested at the level of the PIP joint. Several variations in this technique have been described, including subdividing the long finger FDS into 4 slips for transfer to all 4 fingers, attaching the tendon slips to the flexor tendon sheaths, and attaching the tendon slips to the proximal phalanges through bone tunnels.

**Surgical technique in brief:** The finger FDS tendon or tendons are harvested at the PIP joint or in the palm using traction to ensure adequate length (Fig. 20). Both slips are released, sharply dividing distal to Camper’s chiasm. The superficialis tendon or tendons are withdrawn into the proximal wound, and the longitudinal split in the tendon is extended proximally to create 2 slips of equal caliber.

Skin incisions are made at the dorsoradial bases of the ring and small fingers. The lateral band projecting to each extensor mechanism is identified. Both transferred tendon slips must follow an unimpeded course through the hand, dorsal to the common digital arteries and nerves and palmar to the transverse metacarpal ligaments (Fig. 21). A tendon passer is used to create this path and draw each tendon slip separately to the target finger.

Correct tensioning is achieved with the wrist positioned in extension and the finger MCP joints in maximum flexion, taking up approximately 50% of the excursion of the donor tendons (Fig. 22). After repair, the wrist is brought through a range of motion, demonstrating tenodesis of all finger MCP joints with the wrist flexed. Full passive finger MCP joint extension should be possible with the wrist in extension. The wrist is immobilized postoperatively in approximately 45° of extension with the MCP joints flexed 60° and the IP joints fully extended.

**Tendon transfer for thumb adduction (adductorplasty)**

Restoration of lateral pinch by adductorplasty has been described using various techniques. The most commonly performed procedures include the ECRB and FDS transfers. Brachioradialis, ECRL, EIP, and extensor digiti quinti have also been described. The choice of donor tendon may alter the donor selection for the intrinsicplasty.

**Surgical technique in brief: ECRB thumb adductorplasty:** A series of transverse incisions is made over the dorsoradial border of the extensor retinaculum (Fig. 23).
The insertion of the ECRB is released sharply from the base of the long finger metacarpal and the tendon is withdrawn from beneath the extensor retinaculum. A 2- to 3-cm transverse incision is made over the proximal aspect of the index finger intermetacarpal space, and the fascia overlying the index finger dorsal interosseous muscle is incised. A subcutaneous tunnel is created between the dorsal wrist and hand wounds. A 2- to 3-cm curvilinear incision is then made along the dorsoulnar border of the thumb MCP joint, and the insertion of the adductor pollicis tendon is exposed.

To increase the length of the ECRB tendon, an ipsilateral palmaris longus tendon can be harvested through 2 or 3 small transverse incisions or with the aid of a tendon stripper. Other sources of autogenous tendon graft may be used (eg, plantaris, long toe extensor). Alternatively, the ECRB tendon can be lengthened by longitudinally splitting the tendon in half, leaving the distal 2 cm of tendon intact (Fig. 24). One limb is sectioned proximally through the musculotendinous junction and brought distal to increase the length of the tendon. A curved clamp is passed through the index finger intermetacarpal space volar to the metacarpal and directed toward the thumb MCP joint in the interval between the adductor pollicis and first dorsal interosseous muscles (Fig. 25).

One end of the tendon or tendon graft is sutured to the adductor pollicis tendon at its bony insertion into the phalanx. The other end of the graft is then withdrawn through the index finger intermetacarpal space. The graft is then passed through the subcutaneous tunnel to the proximal wrist incision, dorsal to the extensor retinaculum. With the wrist in neutral alignment and the thumb held tightly against the volar radial border of the index finger, the graft is woven into the previously released ECRB tendon, taking up 50% to 80% of the donor tendon’s excursion. In cases using the ECRB...
split, similar tensioning is performed. With the wrist placed in flexion, the thumb should adduct firmly against the index metacarpal, recreating lateral pinch. With the wrist extended, the thumb should be easily abducted away from the palm. The wrist is splinted in 45° of extension with the thumb in palmar abduction.

Restoration of index finger abduction
Along with thumb adduction, index finger abduction is the second component to generate forceful key pinch. Restoration of first dorsal interosseous function by transferring an accessory slip of abductor pollicis longus or by using the EIP tendon is effective. Loss of ulnar deviation moment provided by the EIP of the index finger, however, can result in an unacceptable, overly abducted posture of the index finger. We do not routinely restore index finger abduction because patients are generally satisfied with restoration of thumb adduction alone for lateral pinch.

Additional tendon transfers for high ulnar nerve palsy
Transfer of the ulnar innervated ring and small FDP tendons to the median innervated FDP index and long tendons will restore IP joint flexion to the ring and small fingers.

Tendon transfers are useful to restore function to the hand impaired and unbalanced by peripheral nerve injury. The limb must have satisfactory tissue equilibrium, and the donor must be carefully selected based on the principles outlined above. Meticulous surgical technique is necessary for optimal outcome. Increasing evidence suggests that supervised rehabilitation after early active, rather than delayed, mobilization protocols is safe and effective.17

REFERENCES