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Review Article

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Upper Limb Reconstruction in Tetraplegic Patients: A Primer for Spinal Cord Injury Specialists

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ABSTRACT

Cervical spinal cord injury (SCI) often causes debilitating loss of function of the upper limb. Upper extremity reconstruction surgery can restore some of the upper limb function in tetraplegic patients with SCI. The procedures are typically muscle-tendon unit transfer surgeries, which redistribute the remaining functional muscles to restore active elbow extension, key grip, and finger grasping. In addition to the tendon transfer surgeries, nerve transfers have emerged recently and are showing promising results. However, despite more than half of the tetraplegic patients can benefit from upper limb surgery, only a few of them receive the procedures. This missed opportunity may be due to the lack of communication between SCI specialists and hand surgeons, or the lack of awareness of such options among the specialists and patients. In this review, we provide a basic overview of upper limb reconstruction in tetraplegic patients with target audience of SCI specialists for their better understanding of the basic concept of surgery and information for patient consultation before referring to hand surgeons.

Keywords: Spinal cord injury; Tetraplegia; Upper extremity; Tendon transfer; Nerve transfer

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Conflict of Interest
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INTRODUCTION

Spinal cord injury (SCI), especially cervical spine involvement, often brings debilitating loss of function of the upper and lower limbs. Tetraplegic patients face many obstacles performing activities of daily living such as feeding, dressing, and hygiene care. Therefore, their upper limbs can be their most essential functional tool.[2)] In a survey of male patients, 75% rated restoration of normal function of the hands are more important than bowel and bladder, legs and sexual function.[27)]

Upper limb reconstruction surgeries were conceptualized more than 40 years ago by Erik Moberg from Sweden.[34)] The surgeries typically involve muscle-tendon unit transfer, which redistribute the remaining functional muscles to restore active *elbow extension, key grip, and finger grasping*. This involves detaching the tendon of a functioning muscle distally and rerouting the muscle to a new distal attachment without damaging its nerve supply. More than half of tetraplegic patients with SCI can benefit from upper limb surgery,[22)] but data in the US showed that only 14% of the surgical candidates received these procedures.[13] A survey in Korean physiatrists and hand surgeons suggested that one of the factors for this missed opportunity is the lack of communication between SCI specialists and hand surgeons.[33] In addition, lack of awareness and accessibility of such options among the doctors and patients forms another barrier in upper limb reconstruction.[14,15,45]

Although several excellent review articles have been published on upper limb reconstruction surgery for tetraplegic patients with SCI, many of them have focused on technical details or complex surgical options according to different injury levels,[5,8,12,22,24,28,29,31,37,39] which might be overwhelming for SCI specialists who are not familiar with hand surgery. We considered that a simpler, SCI specialist-oriented review is necessary for better understanding of the basic concept of surgery and patient-friendly information for consultation before referring to hand surgeons. On the other hand, another surgical option for tetraplegic patients is nerve transfer surgery that have emerged recently, which might be new to even those SCI specialists who are already familiar with the tendon transfer surgeries. Therefore, the purpose of this review is to provide a basic overview of upper limb reconstruction in tetraplegic patients with target audience of SCI specialists.

WHO ARE THE POTENTIAL CANDIDATES?

Tendon transfer surgery is a re-routing technique, where the paralytic muscles are replaced using the remaining functional muscles. In case of nerve transfer, an intact motor nerve innervating a less essential muscle is transferred to reinnervate a paralytic, more essential muscle (**FIGURE 1**). Therefore, not all cervical SCI patients are suitable candidates for surgical management. A potential candidate should have an injury at the levels C5-8 and some expandable donor muscles with Medical Research Council (MRC) Scale for muscle strength grade 4 or more.[3] The common target functions are active elbow extension, key grip, and

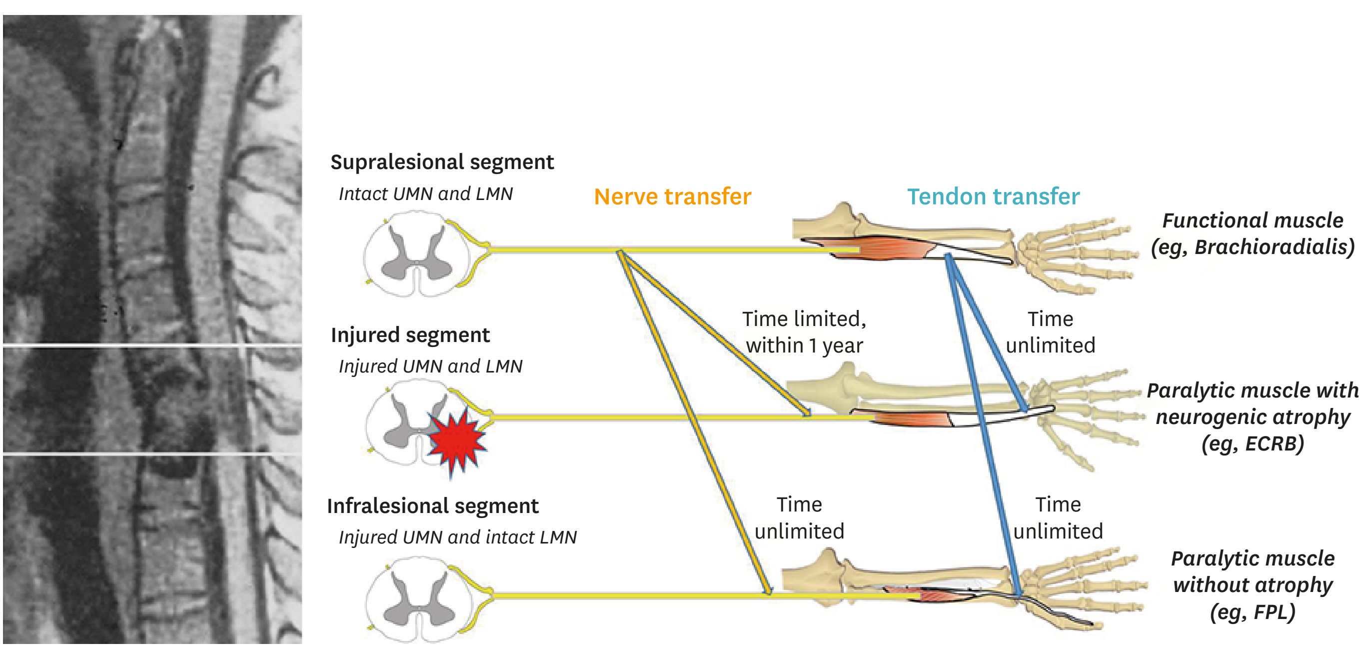

FIGURE 1. The concept of muscle-tendon unit transfer (tendon transfer) and nerve transfer.
UMN: upper motor neuron, LMN: lower motor neuron, ECRB: extensor carpi radialis brevis, FPL: flexor pollicis longus.

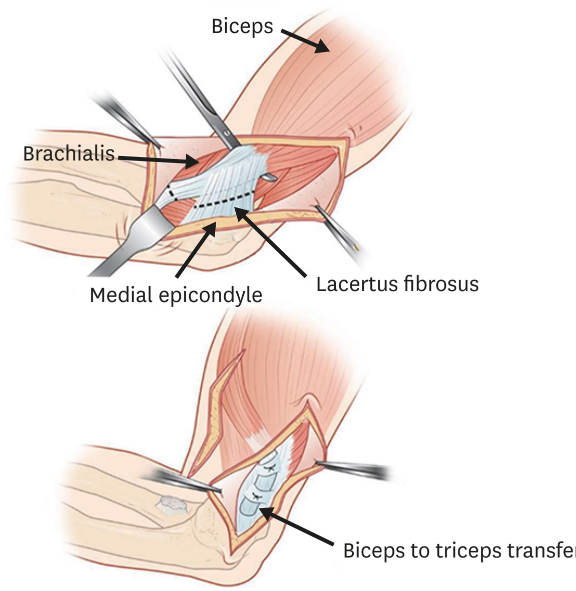

FIGURE 2. Elbow extension reconstruction with biceps to triceps transfer.
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finger grasping for those who lack these functions. Patients must have realistic expectations of the surgical outcome, which is determined by the number of baseline functioning muscles.

Patients suffering from SCI commonly face multiple co-morbidities and psychological instability. The patient must be medically and psychologically stable, no active infection, no joint contractures or spasticity, full passive range of movement of the joints and pain free limb. Good caregiver and psychological support are mandatory as the postoperative immobilization for a few weeks and the necessary rehabilitation give additional burden to both caregivers and patients and the whole process to results will be substantially long.

A classical ideal candidate is a patient with C5-6 injury who cannot actively extend the elbow but has active elbow flexion, and who cannot control the thumb for pinching but has active wrist extension or at least functioning brachioradialis (BR) muscle. Elbow extension reconstruction can be done either by transferring the biceps to the triceps with the remaining brachialis preserving the elbow flexion (**FIGURE 2**) or by transferring the posterior part of the deltoid to the triceps with the remaining anterior part of the deltoid preserving the shoulder elevation (**FIGURE 3**). This can help the patient to propel the wheelchair or self-transfer and reach the hand forward or overhead to expand his/her working space. Key-grip reconstruction (thumb pinching) in this patient can be done by transferring the BR to the thumb flexor muscle (flexor pollicis longus [FPL]), or by fixing the FPL tendon to the radius bone via tenodesis so that the thumb can touch the index finger passively during active extension of the wrist (**FIGURE 4**). This will enable the patient to pick up a fork, pen or do self-clean-intermittent-catheterization.

For patients with more remaining functioning muscles, hand surgeons can do more reconstruction to obtain better upper limb functions, such as fine thumb motion, finger grasping and releasing, or intrinsic muscle functions. Due to the postoperative immobilization position of the limb is different between flexor and extensor reconstructions, the reconstruction procedures are carried out in stages, being first stage for thumb and finger

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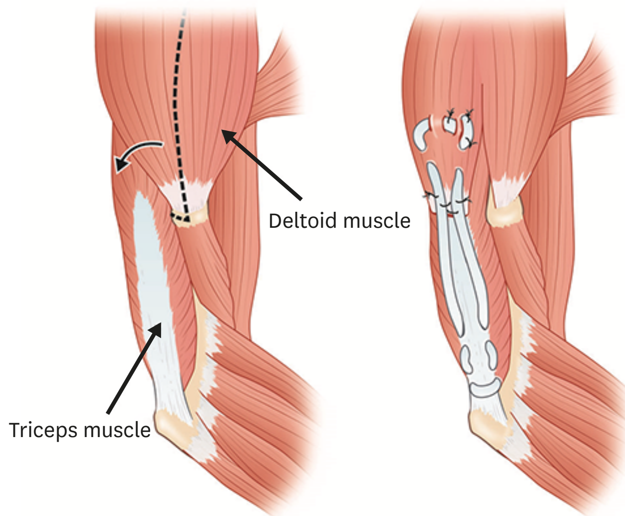

FIGURE 3. Elbow extension reconstruction with posterior deltoid to triceps transfer.
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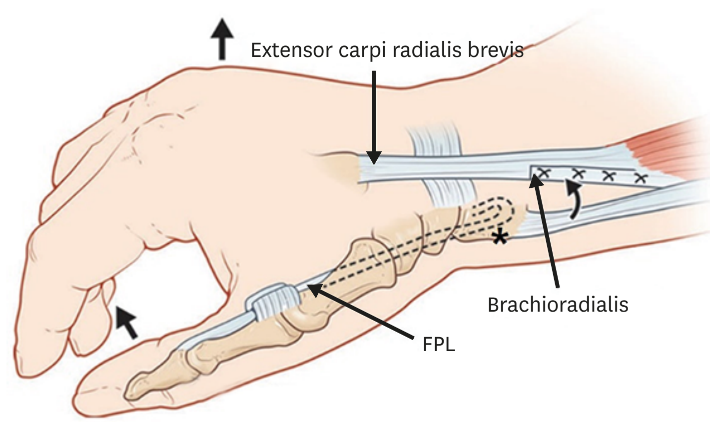

FIGURE 4. Passive key grip reconstruction. If the patient has no or weak wrist extension, the brachioradialis is transferred to the extensor carpi radialis brevis to restore active wrist extension. The FPL is fixed to the distal radius (asterisk). When the patient actively extends the wrist, the thumb passively touches the index finger. Flexing the wrist with gravity opens the thumb web space. If the patient has active wrist extension, the brachioradialis can be transferred to the FPL and active key grip can be possible.
FPL: flexor pollicis longus.
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extension (plus elbow extension when necessary) and second stage for thumb and finger flexion, or vice versa. Those who have chronic injury and accustomed to their remaining function might feel that these complex staged reconstructions are too cumbersome. Therefore, clear understanding of the strategy, recovery time, and staged procedures are crucial information for those patients.

WHEN SHOULD THE SURGERY BE DONE?

It has been established that most neurological recovery generally occurs within 6 months following complete SCI injury.[32] On the other hand, functional recovery in incomplete

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SCI takes longer and thus should not be rushed. Tendon transfer surgeries are usually not considered until patients have reached their plateau for neurological recovery, generally around 12–18 months post SCI. This is a reasonable period for the patient to be managed adequately for other SCI complications e.g. defecation and urinary catheterization, pressure sores healing, tracheostomy weaning, as well as sufficient rehabilitation on a wheelchair and psychological readiness for surgery. It is important to achieve a pain-free full passive range of movement of the joint with no contracture prior to surgery. There is no time limit for tendon transfer surgery after the plateau for neurologic recovery is reached. As mentioned before, however, those who have accustomed to their different style of using the hands may find the rehabilitation after reconstruction is difficult and thus may not be satisfied with the functional gain considering their long recovery period.

In case of nerve transfer, it is important to distinguish between upper and lower motor neuron injury, because after a lower motor neuron injury the muscle soon atrophies with distal axon degeneration. Therefore, nerve transfers for lower motor neuron recovery should be performed before an irreversible muscle atrophy occurs, which is usually after 18 months of denervation (time-dependent, **FIGURE 1**).[17] However, for an upper motor neuron lesion with blockade of central nervous control (below the level of SCI), the lower motor neuron remains intact and the muscle does not undergo atrophy. Therefore, nerve transfers can be performed without a limitation of time window.

WHAT KIND OF TENDON TRANSFER SURGERY CAN BE DONE?

The most important target functions are active *elbow extension, key grip (thumb pinching), and finger grasping.*[35]

Elbow extension reconstruction

Patients with C5-6 injury usually retain shoulder control (C5, deltoid) and elbow flexion (C5, biceps & brachialis) but cannot actively extend the elbow (C7, triceps). Elbow extension is important for overhead activities, weight transfer, wheelchair propulsion and to enable more control of the hand.[41]

For active elbow extension reconstruction, either the biceps (**FIGURE 2**) or the posterior part of the deltoid muscle (**FIGURE 3**) can be transferred to the triceps.[16,30,36] After posterior deltoid transfer, shoulder abduction is preserved by the anterior part of the deltoid. Biceps transfer may compromise elbow flexion and supination. Therefore, the candidate must have intact brachialis and supinator to ensure elbow flexion and supination is retained postoperatively.

Key grip reconstruction

Key grip or lateral pinch between the thumb and index finger is the simplest yet most important hand grasp for patients with SCI. Restoring key grip makes it possible for the patient to do self-clean-intermittent catheterization, which can prevent bladder complication and reduce urinary infection rate.[4]

To reconstruct key grip, active wrist extension must be achieved prior to or together with other procedures if it is absent. Tenodesis effect involves passive movement of distal joints

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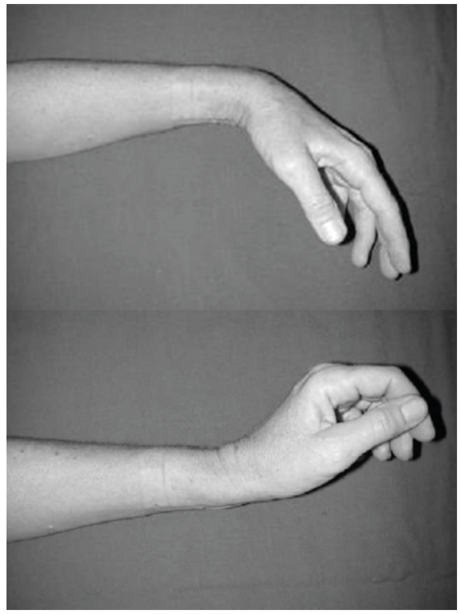

FIGURE 5. Normal tenodesis effect of wrist extension on thumb and finger motion. Key grip reconstruction augments this tenodesis effect to make the thumb firmly touch the index finger.

produced by active movement of the proximal joint in the line of movement of a functioning tendon (**FIGURE 5**). By restoring wrist extension, this tenodesis effect will produce finger flexion and thus achieve key griping and finger grasping.

There are two types of key grip reconstructions: passive key grip and active key grip. If the patient has no active wrist extension and BR muscle is the only available functioning muscle in the forearm, then BR can be transferred to the wrist extensor muscle (extensor carpi radialis brevis [ECRB]). Simultaneously, the tendon of the thumb flexor muscle (FPL) is fixed to the radius. By actively extending the wrist, the patient can passively flex the thumb and firmly touch the index finger (passive key grip, **FIGURE 4**). If the patient has functioning wrist extensors but no functioning FPL, the available BR can be transferred to the FPL and active thumb flexion is possible.[42)]

To improve the precision of thumb-index pinch, several procedures can be combined, such as a fusion for better position of the thumb (thumb carpometacarpal joint arthrodesis),[28)] or a procedure to prevent excessive thumb interphalangeal joint flexion (split FPL tenodesis),[23,24)] and a procedure to improve the position of the index finger (lasso procedure).[44)]

Palmar grasp reconstruction

If the patient has strong active wrist extension and both of the wrist extensor muscles (extensor carpi radialis longus [ECRL] & ECRB) are functioning, the ECRL can be transferred to finger flexor muscles (flexor digitorum profundus [FDP]) to restore palmar grasp.

Opening of the hand, which includes opening the first web and extension of the fingers, is necessary for the hand to surround the object in preparation for grasp. Passive opening of the hand can be achieved via fixing the tendons to bone (tenodesis) by using the thumb extensor (extensor pollicis longus [EPL]) and finger extensors (extensor digitorum communis [EDC]) to the dorsum of the wrist (distal radius or extensor retinaculum). When the patient pronates

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the forearm and the wrist flexes with gravity, the fixed EPL and EDC tendons can passively extend the thumb and fingers.

There are more surgical options for selective functions of the hand especially for patients who have more functioning forearm muscles. These can be discussed with hand surgeons after referral.

WHAT KIND OF NERVE TRANSFER SURGERY CAN BE DONE?

Nerve transfers aim to restore a motor function by coapting an expendable donor nerve under volitional control to reinnervate another more essential muscle. Nerve transfers traditionally were used in brachial plexus and peripheral nerve injuries. Advances in nerve transfers in recent decades have made it an adjunct in the treatment of upper limb tetraplegia.[32] There are a few significant nerve transfer procedures that showed predictable results.[6,7,11,17,18,20,21]

Similar to tendon transfer surgeries, nerve transfers also aim to restore active elbow extension, key grip, and palmar grasp. 'Active' thumb and finger extension can also be restored by nerve transfer whereas 'passive' extension by tenodesis is usually performed in tendon transfer surgery (**FIGURE 6**).

For elbow extension reconstruction, the posterior deltoid branch of the axillary nerve (C5) is transferred to the triceps branch of the radial nerve (C7). Restoration of thumb and finger flexion can be obtained by transfer of the brachialis branch of the musculocutaneous nerve (C5)

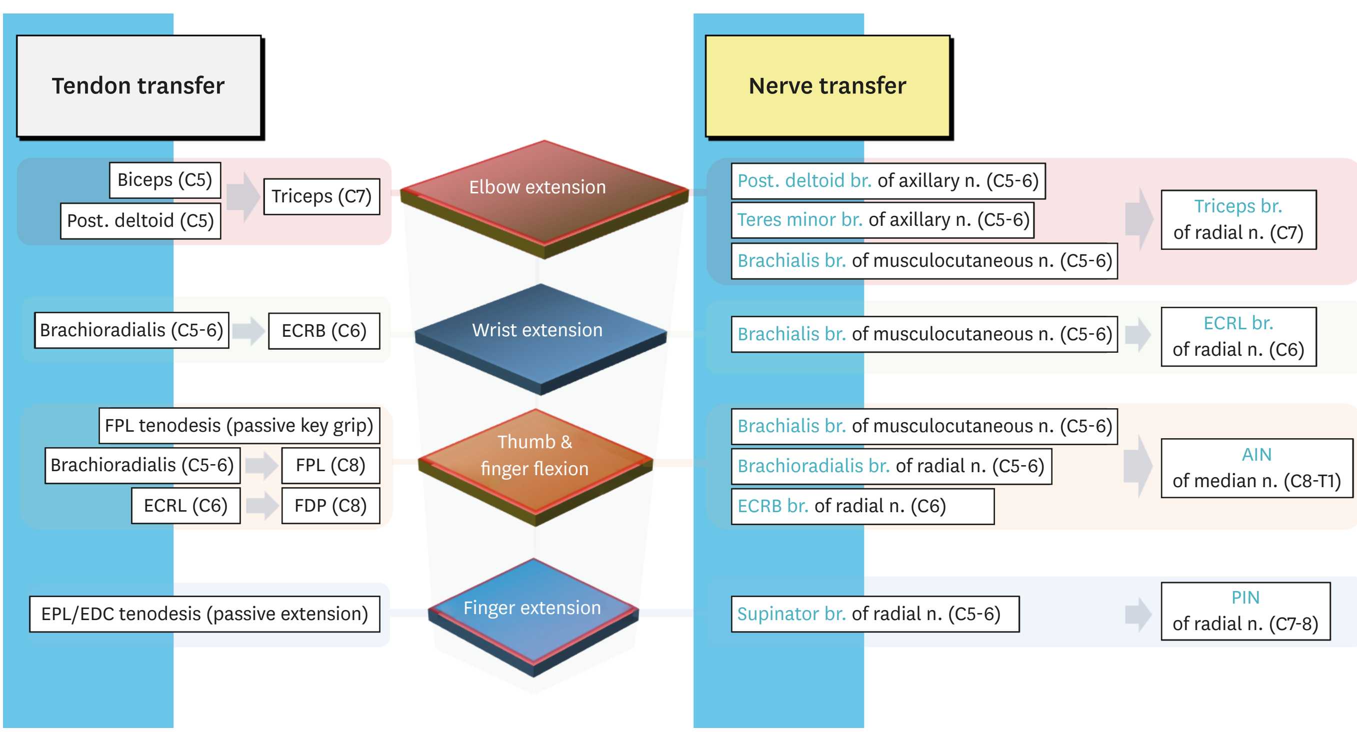

FIGURE 6. Surgical options for tendon transfers and nerve transfers.
ECRB: extensor carpi radialis brevis, FPL: flexor pollicis longus, ECRL: extensor carpi radialis longus, FDP: flexor digitorum profundus, EDC: extensor digitorum communis, AIN: anterior interosseous nerve, PIN: posterior interosseous nerve.

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to the anterior interosseous nerve (AIN) and flexor digitorum superficialis (FDS) fascicles of the median nerve (C7-T1). Restoration of finger and thumb extension is done by using the supinator branch of the radial nerve (C5-6) to the posterior interosseous nerve (PIN) of the radial nerve (C7-8), which is a fascicle transfer in the same radial nerve. As mentioned before, this active thumb and finger extension reconstruction is an attractive advantage in nerve transfer, and thus this can be combined with classical tendon transfer surgeries. Nerve transfer operations may provide options for many injuries that are not amenable to tendon transfers, including those with donor muscle power MRC <4 and those more proximal SCI.[10]

Nerve transfers for elbow, thumb and finger extension are transfers between motor fascicles. These require meticulous identification and intra-neural dissection, e.g. the AIN/FDS fascicles in the median nerve, to avoid inclusion of any sensory fascicles or injury to the functioning motor fascicles.

WHAT ARE THE DIFFERENCES BETWEEN TENDON AND NERVE TRANSFERS?

In addition to the principle and timing of surgery, there are several differences between tendon and nerve transfers (**TABLE 1**).

In tendon transfer surgery, surgeons must consider the excursion of the tendon (how much the muscle can move the joint with contraction) and strength (muscle cross-sectional area) between the donor and recipient muscles. Normally the excursion of the wrist extensor muscle (ECRL) is only 3 cm while that of the finger flexors (FDP) is about 7 cm, thus transferring the ECRL to FDP for finger grasp reconstruction cannot create full flexion of the fingers. Furthermore, fine surgical adjustment of the repair tension (sometimes being referred as an 'art') also affects the outcome of the tendon transfer. On the contrary, nerve transfers do not need to consider tendon excursion and repair tension, as the reinnervated muscles will perform their original function. Therefore, although the reinnervation in nerve transfer can be less reliable than tendon transfer, the restored function, when it works, can be more natural and dexterous with nerve transfer.

For the postoperative care, an important advantage of nerve transfer is that minimal postoperative splinting is required and normal activities can be started after wound healing,

TABLE 1. Comparison between tendon transfer and nerve transfer for upper limb reconstruction

	Tendon transfer	Nerve transfer
Principle	Re-route functioning expandable muscle-tendon unit	Re-innervate target muscle using expandable donor nerve out of injury area
Timing of surgery	No limitation of time window (time-independent)	Rescue surgery within 12–18 months for lower motor neuron injury type (time-dependent)
Staged surgery	Separate stages for flexors and extensors reconstruction	Can be done as single-stage surgery
Targeted movement seen postoperative	After tendon healing and rehabilitation (average 3–6 months)	Time-consuming, up to 1 year or more
Postoperative immobilization	Required for tendon repair healing (4–6 weeks)	Minimal immobilization required
Postoperative rehabilitation	Re-learning to trigger transferred tendon for movement, training of new skills using the transferred tendon (3–6 months)	Co-contraction exercises (activating donor and recipient), motor re-education allowing brain cortical plasticity to take place, focused training
Surgical difficulties	Tendon excursion and tensioning	Meticulous nerve dissection, especially in fascicular transfer
Reliability and reproducibility	More predictable	Less predictable
Complications	Rare; tendon rupture, attenuation, and adhesion	Sacrifice of a non-injured muscle that can be a reliable donor for tendon transfer

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as compared to tendon transfers which require prolonged immobilization of the limb to prevent rupture or attenuation of the repair.

However, a major drawback of nerve transfer is that the patients will not see the immediate effect of reconstruction compared to tendon transfer, as the reinnervation process takes time, sometimes 1 year or more. After the period of immobilization for tendon transfer, rehabilitation involves re-education of the new muscle function and patients generally will be able to gain the function in a few months' time.[40] Whereas in nerve transfer, other than re-innervation of the motor nerve, cortical neuroplasticity in the brain motor cortex can take more time and depend on the proximity of the primary motor areas (homunculus).[38] Therefore, postoperative rehabilitation will have to emphasize motor re-education, co-contraction of both the donor and recipient muscles, and muscle strengthening after successful reinnervation.[1,17]

Complications in tendon transfer are rare, although tendon rupture, attenuation, or adhesion can occur. Nerve transfer sacrifices the original innervation of a non-injured muscle that could be a potential donor for a tendon transfer in the future, e.g. transfer of posterior deltoid branch to triceps nerve will dismiss the deltoid muscle as future tendon transfer donor.[39]

HOW ARE THE RECONSTRUCTIONS HELPFUL?

Wuolle et al.[43] performed a survey in 67 patients who had upper extremity surgery for SCI and found that more than 70% of the participants were generally satisfied with the results and would have the surgery again or recommend the surgery to persons with SCI. In another study regarding long-term patient satisfaction after upper extremity surgery with a survey in 39 patients at a mean follow up of 9 years, 65% of the participants were willing to undergo elbow extension surgery again and 77% expressed their willingness to undergo hand/wrist surgery again.[25] In a systematic review of the literature regarding the outcomes of upper extremity surgery, Hamou et al.[26] reported that the mean MRC grade for elbow extension increased from 0 to 3.3 and the mean postoperative strength for pinch strength increased from 0 to 2 kg after reconstruction.

Bernuz et al.[4] assessed the efficacy of upper extremity surgery on acquisition of intermittent self-catheterization (ISC) in 20 tetraplegic patients with C5-C7 ASIA levels and found that 75% of the patients acquitted the ISC with significant improvement of urinary status. This suggests that the upper extremity surgery may positively affect the health status (longevity) of patients with SCI.

As for nerve transfer results, there are limited literature for comparison and long-term outcome, as this is a relatively novel approach and nerve transfer recovery takes longer period for return of function. In smaller case series and case report, good outcome and little donor deficit were reported.[7,9,11,18,19]

CONCLUSIONS

There are multiple options and procedures that can improve the function of the upper limb in tetraplegic patients. The surgeries are typically muscle-tendon unit transfer surgery, which can redistribute the remaining functional muscle for better active elbow extension, key grip, and finger grasping. Recent emergence of nerve transfers is showing promising results. A potential candidate should be assessed by a qualified hand surgeon and discussed regarding possible options and realistic expectations. A motivated patient with good social support along with coordinated multidiscipline management will bring rewarding results.

REFERENCES

1. Anastakis DJ, Malessy MJ, Chen R, Davis KD, Mikulis D. Cortical plasticity following nerve transfer in the upper extremity. **Hand Clin 24**:425-444, 2008
PUBMED | CROSSREF
2. Anderson KD. Targeting recovery: priorities of the spinal cord-injured population. **J Neurotrauma 21**:1371-1383, 2004
PUBMED | CROSSREF
3. Bednar MS, Woodside JC. Management of upper extremities in tetraplegia: Current concepts. **J Am Acad Orthop Surg 26**:e333-e341, 2018
PUBMED | CROSSREF
4. Bernuz B, Guinet A, Rech C, Hugeron C, Even-Schneider A, Denys P, et al. Self-catheterization acquisition after hand reanimation protocols in C5-C7 tetraplegic patients. **Spinal Cord 49**:313-317, 2011
PUBMED | CROSSREF
5. Bertelli JA, Ghizoni MF. Single-stage surgery combining nerve and tendon transfers for bilateral upper limb reconstruction in a tetraplegic patient: case report. **J Hand Surg Am 38**:1366-1369, 2013
PUBMED | CROSSREF
6. Bertelli JA. Transfer of the radial nerve branch to the extensor carpi radialis brevis to the anterior interosseous nerve to reconstruct thumb and finger flexion. **J Hand Surg Am 40**:323-328.e2, 2015
PUBMED | CROSSREF
7. Bertelli JA, Ghizoni MF. Nerve transfers for elbow and finger extension reconstruction in midcervical spinal cord injuries. **J Neurosurg 122**:121-127, 2015
PUBMED | CROSSREF
8. Bertelli JA, Ghizoni MF. Nerve and free gracilis muscle transfers for thumb and finger extension reconstruction in long-standing tetraplegia. **J Hand Surg Am 41**:e411-e416, 2016
PUBMED | CROSSREF
9. Bertelli JA, Ghizoni MF. Nerve transfers for restoration of finger flexion in patients with tetraplegia. **J Neurosurg Spine 26**:55-61, 2017
PUBMED | CROSSREF
10. Brown JM. Nerve transfers in tetraplegia I: background and technique. **Surg Neurol Int 2**:121-121, 2011
PUBMED | CROSSREF
11. Cain SA, Gohritz A, Fridén J, van Zyl N. Review of upper extremity nerve transfer in cervical spinal cord injury. **J Brachial Plex Peripher Nerve Inj 10**:e34-e42, 2015
PUBMED | CROSSREF
12. Coulet B, Boretto JG, Allieu Y, Fattal C, Laffont I, Chammas M. Pronating osteotomy of the radius for forearm supination contracture in high-level tetraplegic patients: technique and results. **J Bone Joint Surg Br 92**:828-834, 2010
PUBMED | CROSSREF
13. Curtin CM, Gater DR, Chung KC. Upper extremity reconstruction in the tetraplegic population, a national epidemiologic study. **J Hand Surg Am 30**:94-99, 2005
PUBMED | CROSSREF
14. Curtin CM, Hayward RA, Kim HM, Gater DR, Chung KC. Physician perceptions of upper extremity reconstruction for the person with tetraplegia. **J Hand Surg Am 30**:87-93, 2005
PUBMED | CROSSREF
15. Curtin CM, Wagner JP, Gater DR, Chung KC. Opinions on the treatment of people with tetraplegia: contrasting perceptions of physiatrists and hand surgeons. **J Spinal Cord Med 30**:256-262, 2007
PUBMED | CROSSREF
16. Endress RD, Hentz VR. Biceps-to-triceps transfer technique. **J Hand Surg Am 36**:716-721, 2011
PUBMED | CROSSREF
17. Fox IK. Nerve transfers in tetraplegia. **Hand Clin 32**:227-242, 2016
PUBMED | CROSSREF

18. Fox IK, Davidge KM, Novak CB, Hoben G, Kahn LC, Juknis N, et al. Nerve transfers to restore upper extremity function in cervical spinal cord injury: Update and preliminary outcomes. **Plast Reconstr Surg 136**:780-792, 2015
PUBMED | CROSSREF

19. Fox IK, Davidge KM, Novak CB, Hoben G, Kahn LC, Juknis N, et al. Use of peripheral nerve transfers in tetraplegia: evaluation of feasibility and morbidity. **Hand (N Y) 10**:60-67, 2015
PUBMED | CROSSREF

20. Fox IK, Miller AK, Curtin CM. Nerve and tendon transfer surgery in cervical spinal cord injury: Individualized choices to optimize function. **Top Spinal Cord Inj Rehabil 24**:275-287, 2018
PUBMED | CROSSREF

21. Fox IK, Novak CB, Krauss EM, Hoben GM, Zaidman CM, Ruvinskaya R, et al. The use of nerve transfers to restore upper extremity function in cervical spinal cord injury. **PM R 10**:1173-1184.e2, 2018
PUBMED | CROSSREF

22. Fridén J, Gohritz A. Tetraplegia management update. **J Hand Surg Am 40**:2489-2500, 2015
PUBMED | CROSSREF

23. Fridén J, Reinholdt C, Gohritz A. The extensor pollicis longus-loop-knot (ELK) procedure for dynamic balance of the paralyzed thumb interphalangeal joint. **Tech Hand Up Extrem Surg 17**:184-186, 2013
PUBMED | CROSSREF

24. 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 15**:230-235, 2011
PUBMED | CROSSREF

25. Jaspers Focks-Feenstra JH, Snoek GJ, Bongers-Janssen HM, Nene AV. Long-term patient satisfaction after reconstructive upper extremity surgery to improve arm-hand function in tetraplegia. **Spinal Cord 49**:903-908, 2011
PUBMED | CROSSREF

26. Hamou C, Shah NR, DiPonio L, Curtin CM. Pinch and elbow extension restoration in people with tetraplegia: a systematic review of the literature. **J Hand Surg Am 34**:692-699, 2009
PUBMED | CROSSREF

27. Hanson RW, Franklin MR. Sexual loss in relation to other functional losses for spinal cord injured males. **Arch Phys Med Rehabil 57**:291-293, 1976
PUBMED

28. House JH, Comadoll J, Dahl AL. One-stage key pinch and release with thumb carpal-metacarpal fusion in tetraplegia. **J Hand Surg Am 17**:530-538, 1992
PUBMED | CROSSREF

29. House JH, Gwathmey FW, Lundsgaard DK. Restoration of strong grasp and lateral pinch in tetraplegia due to cervical spinal cord injury. **J Hand Surg Am 1**:152-159, 1976
PUBMED | CROSSREF

30. Lacey SH, Wilber RG, Peckham PH, Freehafer AA. The posterior deltoid to triceps transfer: a clinical and biomechanical assessment. **J Hand Surg Am 11**:542-547, 1986
PUBMED | CROSSREF

31. Lamb DW, Chan KM. Surgical reconstruction of the upper limb in traumatic tetraplegia. A review of 41 patients. **J Bone Joint Surg Br 65**:291-298, 1983
PUBMED | CROSSREF

32. Lee SK, Wolfe SW. Nerve transfers for the upper extremity: new horizons in nerve reconstruction. **J Am Acad Orthop Surg 20**:506-517, 2012
PUBMED | CROSSREF

33. Lee SY, Shin HI, Gong HS, Bin SW, Bang MS. Upper extremity reconstruction surgery for the persons with tetraplegia: current status and solutions to promote the procedures in Korea. **J Korean Acad Rehabil Med 32**:175-181, 2008

34. Moberg E. Surgical treatment for absent single-hand grip and elbow extension in quadriplegia. Principles and preliminary experience. **J Bone Joint Surg Am 57**:196-206, 1975
PUBMED | CROSSREF

35. Mohammed KD, Rothwell AG, Sinclair SW, Willems SM, Bean AR. Upper-limb surgery for tetraplegia. **J Bone Joint Surg Br 74**:873-879, 1992
PUBMED | CROSSREF

36. Netscher DT, Sandvall BK. Surgical technique: posterior deltoid-to-triceps transfer in tetraplegic patients. **J Hand Surg Am 36**:711-715, 2011
PUBMED | CROSSREF

37. Reinholdt C, Fridén J. Rebalancing the tetraplegic wrist using extensor carpi ulnaris-tenodesis. **J Hand Surg Eur Vol 38**:22-28, 2013
PUBMED | CROSSREF

38. Socolovsky M, Malessy M, Lopez D, Guedes F, Flores L. Current concepts in plasticity and nerve transfers: relationship between surgical techniques and outcomes. **Neurosurg Focus 42**:E13, 2017
PUBMED | CROSSREF

39. Titolo P, Fusini F, Arrigoni C, Isoardo G, Conforti L, Artiaco S, et al. Combining nerve and tendon transfers in tetraplegia: a proposal of a new surgical strategy based on literature review. **Eur J Orthop Surg Traumatol 29**:521-530, 2019
PUBMED | CROSSREF

40. Wangdell J, Carlsson G, Friden J. From regained function to daily use: experiences of surgical reconstruction of grip in people with tetraplegia. **Disabil Rehabil 36**:678-684, 2014
PUBMED | CROSSREF

41. Wangdell J, Fridén J. Activity gains after reconstructions of elbow extension in patients with tetraplegia. **J Hand Surg Am 37**:1003-1010, 2012
PUBMED | CROSSREF

42. Waters R, Moore KR, Graboff SR, Paris K. Brachioradialis to flexor pollicis longus tendon transfer for active lateral pinch in the tetraplegic. **J Hand Surg Am 10**:385-391, 1985
PUBMED | CROSSREF

43. Wuolle KS, Bryden AM, Peckham PH, Murray PK, Keith M. Satisfaction with upper-extremity surgery in individuals with tetraplegia. **Arch Phys Med Rehabil 84**:1145-1149, 2003
PUBMED | CROSSREF

44. Zancolli E. Structural and dynamic bases of hand surgery. **Am J Phys Med Rehabil 49**:321, 1970

45. Zhong S, Reed GE, Kalliainen LK. Upper extremity surgery in tetraplegia and the online information void. **Hand (N Y)**, Forthcoming 2019
PUBMED | CROSSREF