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Nerve transfers in a patient with asymmetrical neurological deficit following traumatic cervical spinal cord injury: simultaneous bilateral restoration of pinch grip and elbow extension. Illustrative case

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BACKGROUND Cervical spinal cord injury (CSCI) causes severe motor deficit in upper extremities. The mixed segmental CSCI pattern is reflected in the combination of time-sensitive (TS) and non-TS myotomes in the upper extremities. Nerve transfers (NTs) restore upper extremity function yet remain TS procedures. A combination of neurological, magnetic resonance imaging (MRI), and electromyography (EMG) studies allows the identification of TS and non-TS myotomes in the upper extremities.

OBSERVATIONS Nineteen months after NTs, flexor pollicis longus (FPL) and deep flexor of the index finger (FDP2) recovered to M4 (right UE), FPL recovered to M3 and FDP2 to M2 (left EU). The long head of the triceps brachii muscle recovered to M4 bilaterally. The Capabilities of Upper Extremity Questionnaire (CUE-Q) score for unilateral arm functionality increased by 44% (right) and 112.5% (left) and for bilateral arm functionality by 400%; the CUE-Q score for unilateral hand and finger function increased by 283% (right) and 166% (left).

LESSONS The combination of neurological, MRI, and EMG studies before surgery and data obtained during surgery provides reliable information on the CSCI pattern, specifically the availability of motor donor nerves. Simultaneous bilateral restoration is required in the event of CSCI and significantly improves the unilateral and bilateral function of the UEs.

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KEYWORDS cervical spinal cord injury; nerve transfer; anterior interosseous nerve; triceps brachii muscle; radial nerve; spinal accessory nerve

Traumatic spinal cord injury (SCI) is known as one of the most devastating injuries to the structures of the human nervous system.[1] Tissues of the spinal cord (specifically gray and white matter) after SCI are involved in the traumatic process to a different extent in regard to segmental anatomy.[2] Myelomalacia occurs as a result of the direct influence of the traumatic agent on spinal cord tissues.[2] Changes within the gray matter are represented by severely damaged or even dead (due to direct injury or apoptosis[3]) neurons, which are injured metameres (IMs).[2] The segments of the spinal cord located caudal to myelomalacia are represented by viable neurons that have lost their suprasegmental control due to disorganized white matter (axon loss and demyelination[2]) at the level of the IM, infralesional segments (ILSs).[2] The segments of the spinal cord located rostral to the myelomalacia are represented with viable motoneurons, which remain under suprasegmental control, and volitional motor functions are preserved, supralesional segments (SLSs).[2]

By the time phases 1 to 3 of the condition known as "spinal shock" have passed,[4] the neurological deficit in the event of SCI

ABBREVIATIONS Acc-TT = accessory nerve to the transverse part of the trapezius muscle; ADL = activity of daily living; AIN = anterior interosseous nerve; CSCI = cervical spinal cord injury; CUE-Q = Capabilities of Upper Extremity Questionnaire; EMG = electromyography; FDP2 = deep flexor of the index finger; FPL = flexor pollicis longus; ILS = infralesional segment; IM = injured metamere; MRC = Medical Research Council; MRI = magnetic resonance imaging; MSC-B = brachialis motor branch of the musculocutaneous nerve; NT = nerve transfer; SCI = spinal cord injury; SLS = supralesional segment; TB = triceps brachii; TB-Lo = long head of the TB muscle; TS = time sensitive.

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comprises characteristics of both central[5] and peripheral[5] types of paralysis. Motor neurological deficit caused by IMs is reflected in complete or partial peripheral paralysis;[5,6] dysfunctional ILSs cause motor neurological deficit, which is reflected in central paralysis with a complete loss of volitional control over motor functions.[5,6]

One of the most disabling sequelae of cervical SCI is loss of upper extremity function.[7] Recent surveys have shown that the restoration of lost functions of the upper extremity significantly improves the self-care of a patient with tetraplegia. Another study found that recovery of upper extremity function (particularly hand function) was prioritized for restoration of bowel and bladder function or reducing chronic pain and spasticity for survey participants.[8–10] Nowadays, surgical techniques aimed at restoring most prioritized functions of the upper extremity in the event of cervical SCI include tendon transfers, arthrodesis, tenodesis procedures,[1] and, most recently, nerve transfers (NTs).[1,2,11] Potential donor nerves in the event of cervical SCI can be found at the level of SLS: upper and lower motoneurons are intact, and corresponding muscles are under volitional control.[1,2]

It is known that NTs used to manage injuries to the peripheral nervous system depend strongly on the time factor.[12] Myotomes that adhere to IMs in the event of cervical SCI have a similar time dependence; in other words, there is a TS window to restore volitional control in denervated muscles with NT.[13,14] Myotomes that adhere to ILS in the event of cervical SCI are deprived of the time-dependence factor:[5,15] the myotomes preserve their connection with lower motoneurons and maintain tissue integrity and potential for recovery during a long period after the initial injury.[5,11,15]

The area within the spinal cord corresponding to IM and ILS, the true extent of myelomalacia, can be visually confirmed in vivo by means of sequential magnetic resonance imaging (MRI) studies in different regimens.[16] Electrodiagnostics,[17] which comprise combination

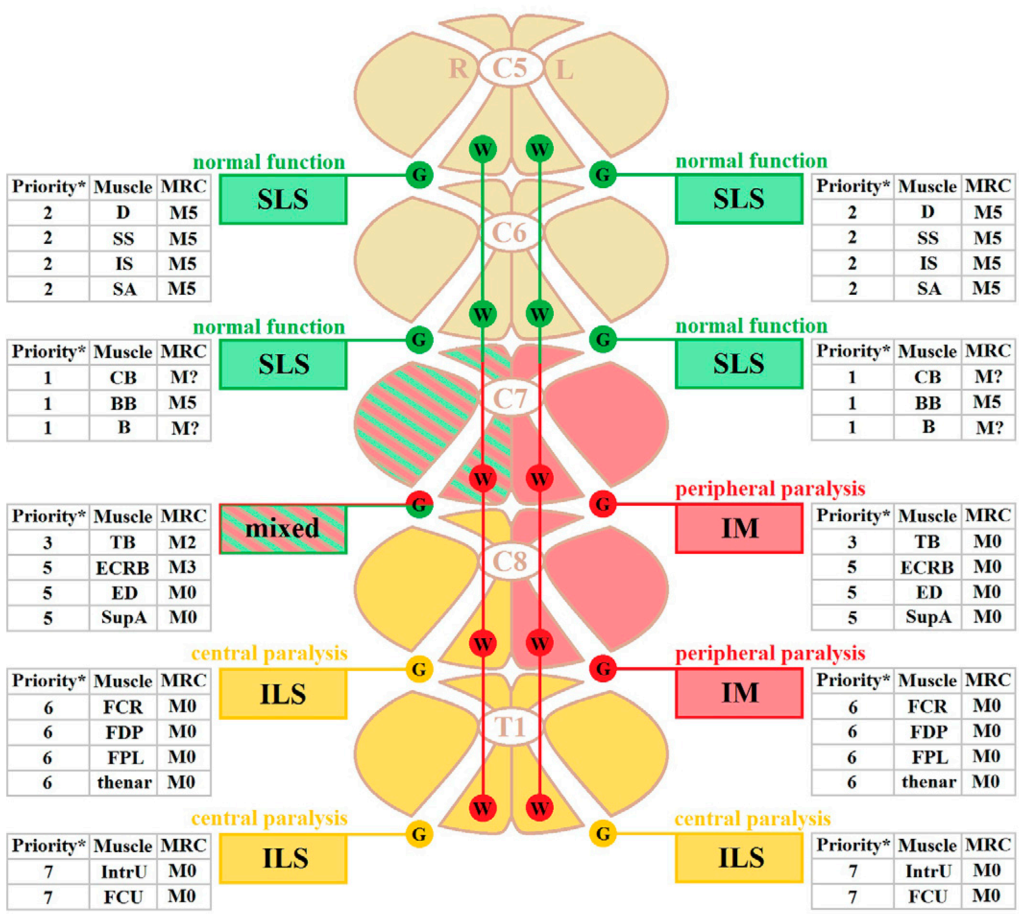

FIG. 1. Schematic presentation of the segmental and longitudinal asymmetry of the cervical SCI, derived from a complex neurological, radiographic, and electrophysiological examination preoperatively. B = brachialis; BB = biceps brachii; CB = coracobrachialis; D = deltoid; ECRB = extensor carpi radialis brevis; ED = finger extensors; FCR = flexor carpi radialis; FCU = flexor carpi ulnaris; FDP = deep finger flexors; G = gray matter, neuronal cells of the anterior horn; IntrU = intrinsics of the hand innervated by ulnar nerve; IS = infraspinatus; L = left upper extremity; mixed = mixed pattern of neurological deficit; R = right upper extremity; SA = serratus anterior; SS = supraspinatus; SupA = supinator antebrachii; thenar = muscles of the thenar; W = white matter, corticospinal tract; 1 = elbow flexion; 2 = shoulder stability, abduction and external rotation; 3 = elbow extension; 5 = wrist and finger extension; 6 = wrist and finger flexion; 7 = ulnar nerve innervated structures; * = the sequence of prioritized functions of the upper extremity, according to Sequeira et al.[25]

of nerve conduction studies (quantitative information) and electromyography (qualitative information), serve as a useful tool to verify the true SCI pattern.[17]

Because most SCI injuries present with a mixed, complex injury pattern,[11] positive clinical results could be achieved if NT were performed shortly after SCI.[18] Relatively early NT helps to reduce the time sensitivity of the muscles related to IM, whereas electrodiagnostic studies serve only as a robust confirmation of the preserved nerve function in SLSs, which can potentially become donors.[5,11,15,18]

Most activities of daily living (ADLs) require bimanual participation,[19] and the roles of the dominant and nondominant upper extremities are different for these ADLs.[19] Paretic upper extremity is majorly used to assist in bimanual ADLs, whereas the unaffected (or less affected) upper extremity is used for unimanual ADLs.[19] It has been determined that the segmental functions of the intact upper extremity are more suitable for performing precision tasks, which require fine motor skills,[20] whereas the segmental functions of the paretic upper extremity are more suitable for performing assistive or complementary tasks, which require less fine motor skills[20] such as holding and stabilizing[21] and providing fixation.[20]

Regardless of the fact that horizontal segmental (in relation to IM/ILS)[2,22] and longitudinal (in relation to the right or left side)[2,22] patterns of cervical SCI (mixed and complex) always exist, relatively early simultaneous reconstruction of the prioritized functions of both upper extremities can potentially provide an adequate and appropriate level of bimanual functional independence for the patient in regard to the longitudinal pattern of cervical SCI.

In this case report, we present simultaneous NTs in a patient with an asymmetrical neurological deficit after a traumatic SCI aimed at restoring the prioritized functions of the proximal and distal segments of both upper extremities.

The purpose of this work was to report on the patient's outcome after bilateral reinnervation of anterior interosseous nerve (AIN) and radial nerve branch to the long head of triceps brachii (TB) muscle, explain the outcome dependency on the pattern of cervical SCI, and describe the level of bimanual functional independence of the patient during ADLs.

Illustrative Case

Clinical Presentation

A 16-year-old right-handed boy was admitted to our department 5 months after a severe cervical SCI at the level of C5–6 vertebrae. The patient received anterior decompression of the spinal cord/dural sac with C5–6 anterior corpectomy followed by C4–7 interbody fusion with titanium mesh and anterior cervical plate in

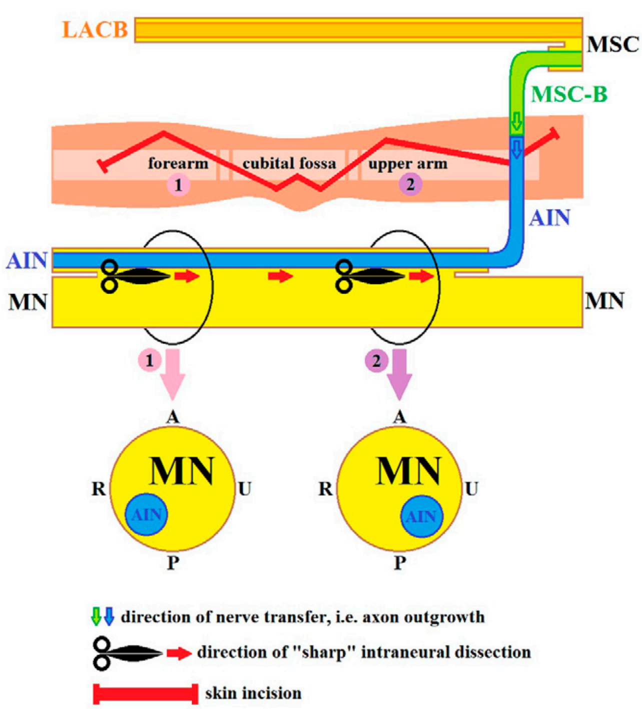

FIG. 2. Schematic representation of the brachialis motor branch to the anterior interosseous NT. A = anterior; LACB = lateral antebrachial cutaneous nerve; MN = median nerve; MSC = musculocutaneous nerve; P = posterior; R = radial side; U = ulnar side; 1 = intraneural fascicular anatomy of the median nerve in the forearm; 2 = intraneural fascicular anatomy of the median nerve in the upper arm.

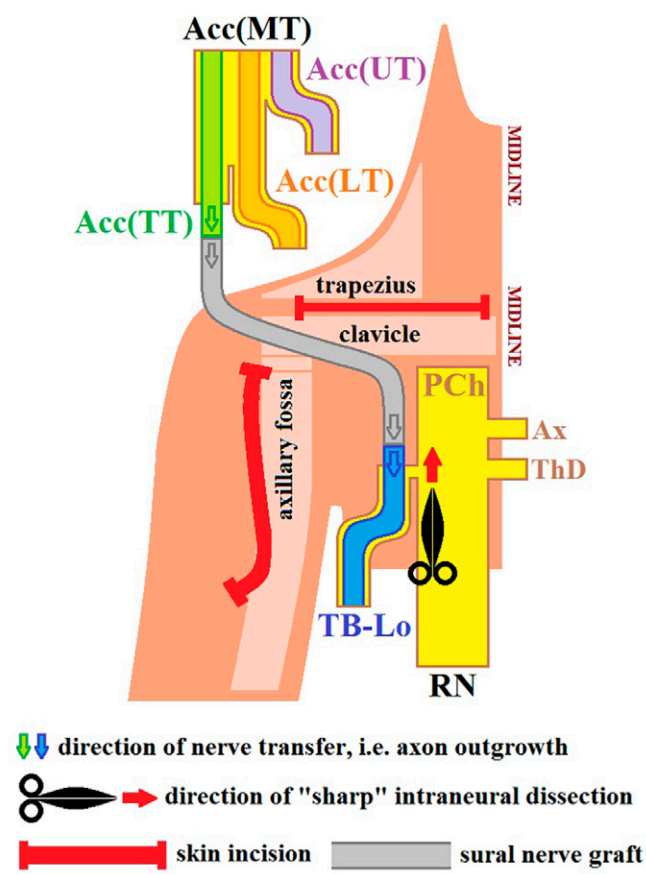

FIG. 3. Schematic representation of the spinal accessory to the long head of the TB muscle NT. Acc(LT) = spinal accessory nerve to the lower trapezius muscle; Acc(MT) = spinal accessory nerve to trapezius muscle; Acc(TT) = spinal accessory nerve to the transverse trapezius muscle; Acc(UT) = spinal accessory nerve to the upper trapezius muscle; Ax = axillary nerve; PCh = posterior cord; ThD = thoracodorsal nerve.

the regional neurosurgical department on the day of injury. Upon admission to our department, neurological examination revealed a motor deficit comprised of asymmetrical paralysis (longitudinal asymmetry) of the muscles innervated by the C7 segment on the right side, with partially preserved volitional function of the long head of the TB (M2 on the Medical Research Council [MRC] scale[23]) and extensor carpi radialis brevis muscle (M3 on MRC), mixed SCI pattern. Complete paralysis of the muscles innervated by the C8–T1 segments with only slight muscular atrophy was diagnosed bilaterally. T1- and T2-weighted MRI studies and electromyography (EMG) studies of the compound muscle action potential[17] of the radial/median nerve and corresponding myotomes allowed confirming segmental asymmetry of the cervical SCI: injured metamere (IM) and ILSs were identified on both sides (Fig. 1). The bilateral functionality of myotomes adhered to the supralesional C6 segment, specifically the function of the biceps brachii and brachialis muscles, was assessed clinically on MRC for the biceps brachii muscle (M5) and needle EMG for the brachialis muscle. Confirmation of the preserved bilateral functionality of the brachialis muscle allowed including its neural supply into the reconstruction plan as donor nerve (Fig. 1). Superficial sensitivity (mainly of a protective type) was partially preserved on the palmar surface of both hands, quantified as S1 on MRC.

Prior to surgery, the patient was asked to complete the Capabilities of Upper Extremity Questionnaire (CUE-Q).[24] The initial scores for the unilateral arm functionality (reach/lift and push/pull) were 25 points (right arm) and 16 points (left arm); bilateral arm functionality was 2 points. The initial score for the unilateral hand and finger functionality was 6 points apiece. The total CUE-Q score for the right and left upper extremities was 34 and 23 points, respectively. The overall CUE-Q score was 61 points.

Taking into account the segmental asymmetry of the neurological deficit following SCI at the time of admission, the probability of a spontaneous regeneration was discussed with the patient in comparison with the NT to either head of the TB on the right and left side at a later date.

Surgical Procedure

The patient was placed supine on the operating table with his head rotated to the contralateral side to the surgical exposure, with abduction in the glenohumeral joint to 45° and extension in the elbow joint to 180°. NT of brachialis motor branch of the musculocutaneous nerve (MSC-B) to the AIN of the median nerve (Step 1) was followed by NT of the branches of the spinal accessory nerve to the transverse part of the trapezius muscle (Acc-TT) via anterior approach to the branch of the radial nerve to the long head of the TB muscle (TB-Lo) in the axillary groove through the sural nerve graft (Step 2). Both Step 1 and Step 2 procedures were performed on the same day for each given side. The time interval for simultaneous NT on the right and left sides was 2 weeks.

Step 1

NT of MSC-B to AIN was performed in full accordance with the technique presented by Ray et al.[26] Anastomosis between MSC-B and AIN was performed with the help of microscopic magnification (×5–8) with 9–0 nonabsorbable monofilament sutures in a tension-free manner. A schematic representation of the procedure is shown in Fig. 2.

Step 2

NT of Acc-TT to TB-Lo was performed in full accordance with the technique presented by Bulstra et al.[27] Anastomosis among Acc-TT, sural nerve graft, and TB-Lo was performed with the help of microscopic magnification (×5–8) with 9–0 nonabsorbable

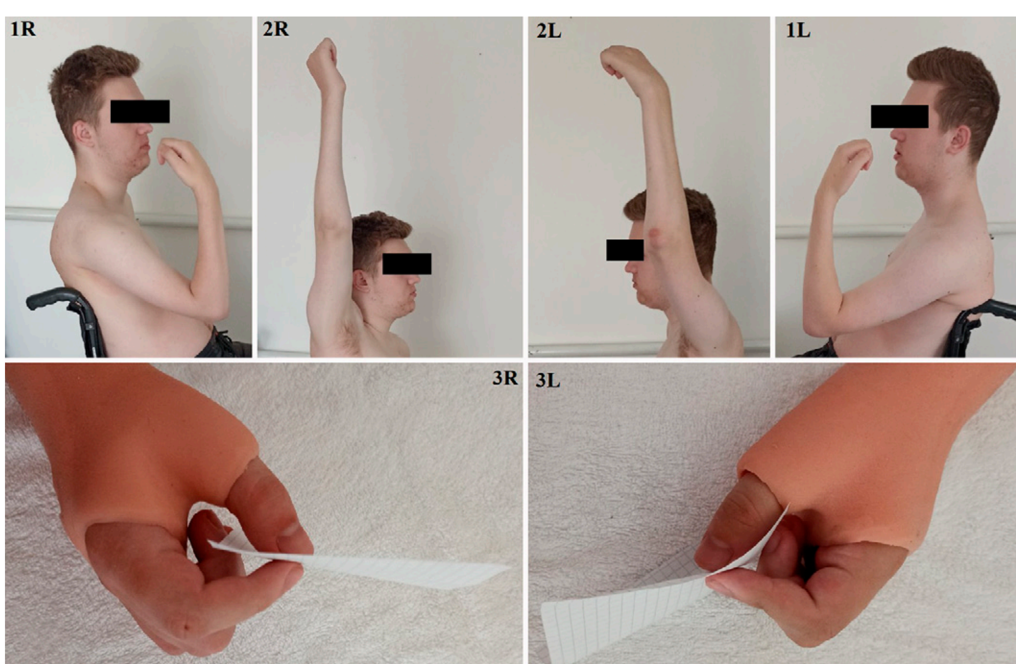

FIG. 4. Recovered functions of the right and left upper extremity 19 months following the simultaneous NTs used in this case. L = left upper extremity; R = right upper extremity; 1 = elbow flexion, mediated by the remaining biceps brachii muscle following harvesting of the brachialis branches of musculocutaneous nerve; 2 = elbow extension mediated by the recovered TB-Lo muscle following NT; 3 = functioning of the FPL and deep flexor of the index finger following NT.

monofilament sutures in a tension-free manner. A schematic representation of the procedure is shown in Fig. 3.

Discussion

Observations

Follow-up examinations of this patient were conducted 12 and 19 months after surgery. At 19 months postoperatively, the long head of the TB muscle recovered to M4 on both sides following the NT of Acc-TT to TB-Lo (Fig. 4, 1R and 1L), whereas the right extensor carpi radialis brevis muscle remained M3 and showed no progression in recovery (Fig. 4, 2R). Flexor pollicis longus (FPL) and deep flexor of the index finger (FDP2) recovered to M4 following NT of MSC-B to AIN on the right side (Fig. 4, 3R). FPL recovered to M3 and FDP2 to M2 on the left side (Fig. 4, 3L). The patient required an external orthosis to provide wrist stability and thumb opposition (Fig. 4, 3R and 3L).

At 19 months, the patient was asked to complete the CUE-Q. The score for unilateral arm functionality (reach/lift and push/pull) reached 36 points (44% increase for the right arm) and 34 points (112.5% increase for the left arm); bilateral arm functionality was 10 points (400% increase). The score for the unilateral right hand and finger function reached 23 points (283% increase); the unilateral left hand and finger function was 16 points (166% increase). The total CUE-Q score for the right and left upper extremities was 62 (82% increase) and 53 (130% increase) points, respectively. The overall CUE-Q score reached 124 points (103% increase).

Lessons

Planning reconstruction with NTs of the most prioritized motor functions of the upper extremity is a challenging task because of the asymmetry of the neurological deficit following cervical SCI.[2,5,6] The mixture of injury patterns,[2,5,11,15,22] both of longitudinal[2,22] and segmental[2,22] origins, poses two main challenges for successful NT: (1) identification of IM and ILSs in regard to the long-term preservation of viability of target muscles[5,15] and (2) identification of donor nerves with preserved functionality, located close enough to the target muscle, in regard to the potential mixture of the injury pattern within one SLS.

According to the results obtained in this case, we state the following: complex neurological, MRI, and EMG studies at the preoperative stage provide reliable information on SCI pattern for IMs and ILSs (Fig. 5). The established SCI pattern allows identifying TS target muscles to perform early NTs (Fig. 5). Needle EMG at the preoperative stage failed to recognize a mixed pattern of injury (partially IM) within C6 segment on the left (Fig. 1 versus Fig. 5). The mixed injury pattern within C6 segment on the left was revealed during surgery (intraoperatively) and was reflected in a reduced contractility of the brachialis muscle compared to biceps brachii

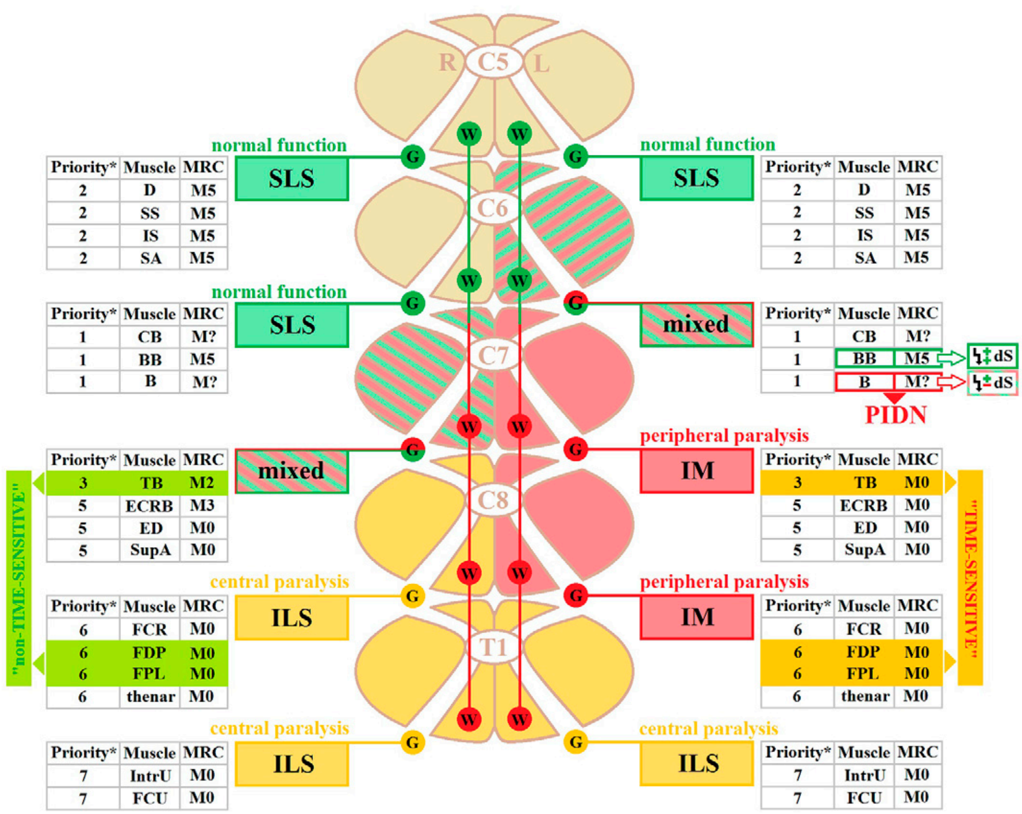

FIG. 5. Schematic presentation of segmental and longitudinal asymmetry of the cervical SCI, derived from a complex neurological, radiographic, electrophysiological examination preoperatively and intraoperatively. D = deltoid; dS = direct electrical stimulation of MSC-B intraoperatively; +/– = reduced contractile ability of brachialis muscle compared to the biceps brachii muscle (+/+); PIDN = partially injured donor nerve; 1 = elbow flexion; 2 = shoulder stability, abduction and external rotation; 3 = elbow extension; 5 = wrist and finger extension; 6 = wrist and finger flexion; 7 = ulnar nerve innervated structures; * = sequence of prioritized functions of the upper extremity according to Sequeira et al.[25]

muscle during direct electrical stimulation of the corresponding nerve branches of the musculocutaneous nerve (Fig. 5). The use of partially injured donor nerves[28] can still provide recovery to denervated muscles (Fig. 4, 3L) but, as expected, to a much lesser extent power-wise. Harvesting of motor branches to the brachialis muscle neither reduced the power of elbow flexion generated by the remaining biceps brachii muscle nor decreased the angular deviation during elbow flexion (Fig. 4, 1R and 1L). Extraplexual NTs at cervical SCI help significantly improve the functionality of the proximal segments (arm) of the upper extremity and, respectively, their use to perform basic ADLs. Restoration of forearm (pronation/supination), hand, and finger functions depends highly on the injury pattern of the cervical spinal cord (availability of expendable intraplexual motor donor nerves). Wrist functionality and functions of intrinsics (specifically thumb) can be partially recompensed by external stabilizing orthotic devices (Fig. 4, 3R and 3L). Simultaneous (in time perspective) bilateral restoration of prioritized functions of the upper extremity is required in the event of segmental and longitudinal asymmetry at cervical SCI. Simultaneous reinnervation allows use of a more functional upper extremity for performing precision tasks, whereas a more paretic upper extremity is available for performing assistance or complementary tasks during bimanual ADLs at the time of recovery.

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: Gatskiy Acquisition of data: Gatskiy, YV Tsymbaliuk. Analysis and interpretation of data: Gatskiy, Tretyak, YV Tsymbaliuk. Drafting the article: Gatskiy, Tretyak, VI Tsymbaliuk. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Gatskiy. Administrative/technical/material support: VI Tsymbaliuk, YV Tsymbaliuk. Study supervision: VI Tsymbaliuk.

Supplemental Information

Online-Only Content

Supplemental material is available with the online version of the article.

Supplementary Fig. 1. https://thejns.org/doi/suppl/10.3171/CASE22301.

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