www.nature.com/sc

ARTICLE

Spontaneous Motor Recovery after Cervical Spinal Cord Injury: Issues for Nerve Transfer Surgery Decision Making

Jana Dengler[1,2], John D. Steeves[3], Armin Curt[4], Munish Mehra[5], Christine B. Novak[2], DOD consortium*, EMSCI consortium* and Ida K. Fox[6,7]✉

STUDY DESIGN: Retrospective cohort study.

OBJECTIVES: To quantify spontaneous upper extremity motor recovery between 6 and 12 months after spinal cord injury (SCI) to help guide timing of nerve transfer surgery to improve upper limb function in cervical SCI.

SETTING: Nineteen European SCI rehabilitation centers.

METHODS: Data was extracted from the European Multicenter Study of SCI database for individuals with mid-level cervical SCI ($N = 268$). Muscle function grades at 6 and 12 months post-SCI were categorized for analysis.

RESULTS: From 6 to 12 months after SCI, spontaneous surgically-relevant recovery was limited. Of all limbs ($N = 263$) with grade 0–2 elbow extension at 6 months, 4% regained grade 4–5 and 11% regained grade 3 muscle function at 12 months. Of all limbs ($N = 380$) with grade 0–2 finger flexion at 6 months, 3% regained grade 4–5 and 5% regained grade 3 muscle function at 12 months.

CONCLUSION: This information supports early (6 month) post-injury surgical consultation and evaluation. With this information, individuals with SCI can more fully engage in preference-based decision-making about surgical intervention versus continued rehabilitation and spontaneous recovery to gain elbow extension and/or hand opening and closing.

Spinal Cord (2022) 60:922–927; https://doi.org/10.1038/s41393-022-00834-6

INTRODUCTION

Surgery can restore elbow extension and hand opening and closing in people with mid-level cervical spinal cord injury (SCI). Options include tendon transfers [1], which can be performed many years post-SCI; and nerve transfers [2, 3], which may be more time-sensitive.

In nerve transfer surgery, an expendable peripheral donor nerve branch is transferred to a non-functioning recipient nerve. The donor nerve comes from above the spinal cord injury and is under volitional control; the recipient nerve is not under volitional control, has upper motor neuron (UMN) dysfunction and may or may not have concomitant lower motor neuron (LMN) dysfunction [4].

Our previous work found that LMN dysfunction is present: 1) in 37% of individuals presenting for transfer to restore hand closing; 2) in 57% of individuals presenting for transfer to restore hand opening; and 3) in all individuals presenting for transfer to restore elbow extension [5]. Another study reported that 87% of tested nerve transfer recipient muscles had LMN dysfunction [6].

Based on the experience treating peripheral nerve injury, early intervention within months of injury is critical to reinnervation and restoration of function [7]. However, in cervical SCI, spontaneous recovery of motor function occurs within this same time period [8, 9].

The pathophysiology of spontaneous recovery in SCI is complex and multimodal, with changes within central pathways, the spinal cord, and nerve roots [10, 11]. Previous studies have examined spontaneous recovery within the first year of SCI and suggest that 1) rapid recovery occurs in the first 3 months, 2) the majority of recovery occurs during the first 6 months, 3) there is minimal recovery between 6 and 12 months post-SCI [8, 9], and 4) it occurs within the two spinal segments caudal to the initial motor level [12, 13]. Recovery in incomplete SCI, however, is more substantial, and more variable [9, 12]. It is imperative to provide more detailed information on the extent of motor recovery that may occur during the 6-12 months period post-SCI, when the opportunity for nerve transfer surgery is most favorable.

The primary aim of this study was to quantify the extent of spontaneous upper extremity motor recovery between 6 and 12 months after cervical SCI. The secondary aim was to assess the impact of age, gender and American Spinal Injury Association (ASIA) Impairment Scale (AIS) category on motor recovery. The ultimate goal of this research was to provide clinicians information

---

[1]Division of Plastic and Reconstructive Surgery, Tory Trauma Program, Sunnybrook Health Sciences Centre, University of Toronto, Toronto, Ontario, Canada. [2]University of Toronto, Division of Plastic & Reconstructive Surgery, Toronto, Ontario, Canada. [3]ICORD, University of British Columbia, Vancouver British Columbia, Vancouver, Canada. [4]Spinal Cord Injury Center, Balgrist University Hospital, Zurich, Switzerland. [5]Tigermed-BDM Inc, Gaithersburg Maryland, Maryland, USA. [6]Division of Plastic and Reconstructive Surgery, Department of Surgery, Washington University School of Medicine, St Louis Missouri, USA. [7]VA St. Louis Healthcare System, St Louis Missouri, USA. *Lists of authors and their affiliations appear at the end of the paper. ✉email: foxi@wustl.edu

Received: 12 November 2021 Revised: 28 June 2022 Accepted: 30 June 2022

to discuss expectations for spontaneous recovery of upper extremity motor function when counseling individuals about early (6-12 months post-SCI) nerve transfer surgery.

MATERIALS AND METHODS

Institutional Review Board approval was obtained at the individual SCI centers participating in the European Multicenter Study of SCI (EMSCI). To maintain compliance with HIPAA (Health Insurance Portability and Accountability Act) and GDPR (General Data Protection Regulation), the identity of the person was never searched or obtained for this study. This retrospective cohort study was conducted according to the principles of the Declaration of Helsinki.

Data

This study used data acquired from the EMSCI database to compare muscle function at 6 and 12 months after cervical SCI injury. The database includes rigorously and prospectively collected neurological and functional independence measurements provided by SCI rehabilitation centers participating in the study group (www.emsci.org, ClinicalTrials.gov Identifier NCT01571531). Participants with acute SCI are examined by trained clinicians according to a uniform protocol within the first 2 weeks of injury and at 1, 3, 6, and 12 months after SCI.

Cohort

A cohort was constructed of all EMSCI participants with cervical SCI. Age at time of injury, sex, mechanism of injury, and AIS grade at 6 and 12 months was recorded. Muscle function grading for each limb at 6 and 12 months was collected and analyzed. Each limb (left and right) of the participants was considered individually.

Muscle function

We used the International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI) [14], and included muscle function grading of spinal cord segments as follows: 0 = total paralysis, 1 = palpable or visible contraction, 2 = active movement, full range of motion (ROM) with gravity eliminated, 3 = active movement, full ROM against gravity, 4 = active movement, full ROM against gravity and moderate resistance in a muscle-specific position, 5 = normal active movement, full ROM against gravity and full resistance in a functional muscle position expected from an otherwise non-impaired person.

Inclusion and exclusion criteria

Limbs that would be potential candidates for nerve transfer surgery of the upper extremity were included for analysis. These were limbs with muscle function grade 3, 4, or 5 at the relevant segment with all rostral levels having grade 4 or 5 and all caudal levels having grade 0, 1 or 2. Limbs with incomplete muscle grading data at 6 or 12 months were excluded. We purposefully only included participants, where muscle function caudal to the key functional cervical motor level was 0–2, as those with mixed function below the level likely, are not appropriate surgical candidates.

Spontaneous recovery of function

The tested key muscles were assigned to the following spinal cord segments: biceps-C5, wrist extension-C6, elbow extension-C7, digit flexion-C8, and little finger abduction-T1 [14]. We compared change in the more caudal segments' muscle function at 6 and 12 months post-SCI. Muscle function was categorized as: 0, 1 or 2 (non-functional muscle contraction), 3 (anti-gravity muscle contraction alone), and 4 or 5 (strong muscle contraction). We analyzed the impact of age, gender, and AIS status on this recovery.

Statistical analysis

Descriptive statistics were used to summarize baseline characteristics. Recovery of caudal segment muscle function 12 months after SCI is reported with 95% confidence intervals for each group. The Fisher's Exact Test is used to compare muscle function recovery for the following groups: (1) age < 40, age 40–60, and age > 60 years, (2) female and male, and 3) motor complete (AIS A/B) and motor incomplete (AIS C/D) patterns of injury. Alpha < 0.05 was considered statistically significant.

RESULTS

Demographic data

There were a total of 268 participants available for analysis; but only 449 (of the 536) limbs met the surgically relevant motor level definition given above. Average age was 42 ± 17 years; 20% were female. The most common cause of SCI was trauma (97%). Participants were categorized on the basis of 6-month AIS grade as follows: A 38%, B 19%, C 19%, D 24%.

Muscle function at six months

As defined above, we identified limbs with muscle function grade 3, 4, 5 at a specific segment with all rostral function grade 4, 5 and all caudal function 0, 1, 2. Thus a limb with a "C7 functional motor level" would have (1) C7 elbow extension grade 3, 4 or 5 and (2) rostral C5 elbow flexion and C6 wrist extension grade 4 or 5 and (3) caudal C8 finger flexion and T1 little finger abduction grade 0, 1, or 2. Overall, at six months: 112 limbs (25%) were functional C5; 151 limbs (34%) were C6; 117 limbs (26%) were C7; and 69 limbs (15%) were C8 as per our surgically relevant definition. Table 1.

Muscle function at twelve months

At 12 months post SCI, very few of these limbs regained additional strong (grade 4, 5) caudal muscle strength. Recovery of muscle function (with the corresponding 95% confidence intervals) for each of the groups of limbs is presented in Tables 2 and 3 and in Supplementary Figs. 1 and 2. Data for those limbs that *started* (at 6 months) with muscle strength grade 4, 5 is shown separately (Supplementary Fig. 1) from those that *started* with muscle strength grade 3 (Supplementary Fig. 2). Data for those limbs that *gained* muscle strength grade 4, 5 is shown separately from those

Table 1. Demographic Data.

	Participants *n* = 268	**Limbs *n* = 449**
Age (mean ± standard deviation)	42 ± 17 years	41 ± 17 years
Gender, *n* (%)		
Male	215 (80%)	358 (80%)
Female	53 (20%)	91 (20%)
Mechanism of Injury, *n* (%)		
Traumatic	261 (97.3%)	437 (97.3%)
Ischemic	6 (2.2%)	11 (2.5%)
Other	1 (0.4%)	1 (0.2%)
American Spinal Injury Association Impairment Scale category at 6 months, *n* (%)		
AIS A	98 (38%)	180 (42%)
AIS B	49 (19%)	86 (20%)
AIS C	49 (19%)	85 (20%)
AIS D	61 (24%)	78 (18%)
Functional motor level at 6 months, *n* (%)*		
C5	68 (25%)	112 (25%)
C6	79 (30%)	151 (34%)
C7	71 (26%)	117 (26%)
C8	50 (19%)	69 (15%)

*The surgically relevant functional motor level (C5-8) at 6 months post-SCI was defined as: limbs with muscle function grade 3, 4, 5 at the specific level with all rostral function grade 4, 5 and all caudal function grade 0, 1, 2. Participants were assigned a functional motor level based on the extremity with the highest level of function. Therefore, an individual with asymmetric function (functional C5 on the right and C6 on the left upper extremity) would be categorized as having a C6 functional motor level.

Table 2. Recovery of motor function at 12 months after SCI for each of the groups of limbs starting with *strong* motor level of grade 4, 5 at 6 months.

Baseline Functional Motor Level (6 mo.)	Recovery of Functional Motor Level (12 mo.)	*n*	Motor Recovery (Muscle Function Grade) with 95% CI (%)		
			4 or 5	3	0, 1 or 2
C5	C5	85	92 ± 6%	8 ± 6%	0%
	C6	85	5 ± 5%	19 ± 8%	76 ± 9%
	C7	85	1 ± 2%	5 ± 5%	94 ± 5%
	C8	85	2 ± 3%	1 ± 2%	96 ± 4%
	T1	85	0 ± 0%	1 ± 2%	99 ± 2%
C6	C6	100	93 ± 5%	6 ± 5%	1 ± 2%
	C7	100	8 ± 5%	16 ± 7%	76 ± 8%
	C8	100	2 ± 3%	1 ± 2%	97 ± 3%
	T1	100	0 ± 0%	0 ± 0%	100 ± 0%
C7	C7	80	94 ± 5%	4 ± 4%	3 ± 3%
	C8	80	9 ± 6%	15 ± 8%	76 ± 9%
	T1	80	4 ± 4%	6 ± 5%	90 ± 7%
C8	C8	36	81 ± 13%	8 ± 9%	11 ± 10%
	T1	36	22 ± 14%	25 ± 14%	53 ± 16%

C Cervical, *CI* Confidence interval, *MO* Months, *SCI* Spinal cord injury.

Table 3. Recovery of motor function at 12 months after SCI for limbs starting with *anti-gravity* motor level of grade 3 at 6 months.

Baseline Anti-gravity Motor Level (6 mo.)	Recovery of Functional Motor Level (12 mo.)	*n*	Motor Recovery (Muscle Function Grade) with 95% CI (%)		
			4 or 5	3	0, 1 or 2
C5	C5	27	52 ± 19%	37 ± 18%	11 ± 12%
	C6	27	0 ± 0%	19 ± 15%	81 ± 15%
	C7	27	0 ± 0%	11 ± 12%	89 ± 12%
	C8	27	0 ± 0%	4 ± 7%	96 ± 7%
	T1	27	0 ± 0%	0 ± 0%	100 ± 0%
C6	C6	51	29 ± 13%	67 ± 13%	4 ± 5%
	C7	51	2 ± 4%	12 ± 9%	86 ± 9%
	C8	51	0 ± 0%	2 ± 4%	98 ± 4%
	T1	51	0 ± 0%	0 ± 0%	100 ± 0%
C7	C7	37	46 ± 16%	46 ± 16%	8 ± 9%
	C8	37	3 ± 5%	11 ± 10%	86 ± 11%
	T1	37	0 ± 0%	8 ± 9%	92 ± 9%
C8	C8	33	33 ± 16%	52 ± 17%	15 ± 12%
	T1	33	12 ± 11%	21 ± 14%	67 ± 16%

C Cervical, *CI* Confidence interval, *MO* Months, *SCI* Spinal cord injury.

that gained muscle strength grade 3 (these data are presented in columns within each figure). The data for both the starting level and the more caudal levels are presented.

Overall, the majority of recovery occurred at the adjacent caudal spinal cord segment. Of limbs with strong C5 (grade 4, 5) at 6 months post-SCI (and weak caudal function), 5% gained strong (grade 4, 5) and an additional 19% gained anti-gravity (grade 3) C6 function (Table 2 and Supplementary Fig. 1). Of limbs with strong C5 *and* C6 function (grade 4, 5) at 6 months post-SCI (and weak caudal function), 8% gained strong (grade 4, 5) and an additional 16% gained anti-gravity (grade 3) C7 function. Of limbs with strong C5, C6 and C7 function (grade 4, 5) at 6 months post-SCI (and weak caudal function), 9% gained strong (grade 4, 5) and an additional 15% gained anti-gravity (grade 3) C8 function. Finally, of limbs with strong C5, C6, C7 and C8 function (grade 4, 5) at 6 months post-SCI (and weak caudal function), 22% gained strong (grade 4, 5) and an additional and 25% gained anti-gravity (grade 3) T1 function.

There were some changes *at* the defined functional motor level of interest. There was greater variability for limbs starting with grade 3 compared to grade 4, 5 function at the defined level; for example, of those limbs that started at grade 3 functional C5 ($N = 27$), 52% gained grade 4, 5; 37% remained at grade 3 and 11% decreased to grade 0, 1, 2. In comparison, of the limbs that started at grade 4, 5 functional C5 ($N = 85$), 92% remained at grade 4, 5; 8% decreased to grade 3 and none to grade 0, 1, 2. These data are presented in Table 2 (for those limbs that started with muscle strength grade 4, 5) and Table 3 (for limbs that started with muscle strength grade 3) in the first row for each defined functional motor level of interest.

Summarized surgically relevant motor recovery results for elbow extension and hand closing

Of the limbs with minimal wrist extension (C6) function at 6 months (grade 0, 1 or 2, $n = 149$ limbs), 9% regained strong (grade 4, 5) wrist extension function at 12 months, and an additional 20% regained antigravity (grade 3) wrist extension function. Of the limbs with minimal triceps (C7) elbow extension function at 6 months (grade 0, 1 or 2, $n = 294$ limbs), 6% regained strong (grade 4, 5) triceps function at 12 months, and an additional 13% regained antigravity (grade 3) triceps function. When examining the limbs of *all* participants with minimal hand function at 6 months (C8, finger flexion, $n = 449$ limbs), 5% regained strong (grade 4 or 5) finger flexion at 12 months, and an additional 8% regained anti-gravity (grade 3) finger flexion function. When examining the limbs of *all* participants with minimal intrinsic (T1) function at 6 months (grade 0, 1, or 2, $n = 539$ limbs), 4% regained strong (grade 4, 5) intrinsic function at 12 months, and an additional 8% regained antigravity (grade 3) intrinsic function. This includes limbs with at least C5 muscle function grade 4, 5 only. Individuals with a functional motor level rostral to C5 at 6 months after injury were not included in the analysis as these individuals would not be appropriate surgical candidates due to the absence of suitable donors. See Supplementary Table 1, for a patient-language summary of these findings that can be given to potential surgery candidates.

Subgroup analysis of motor recovery

Subgroup analysis showed greater recovery rates for individuals with incomplete spinal cord injury (AIS C or D; C5 functional motor level, $p < 0.02$ for recovery of C6-T1; C6 functional motor level, $p < 0.007$ for recovery of C7-T1; C8 functional motor level, $p = 0.005$ for recovery of T1). Age and gender did not significantly affect motor recovery. Further subgroup analysis evaluating the differences in recovery at the more caudal segments was also performed. There were no significant differences in the recovery at each caudal segment at 12 months starting with grade 2 compared with grade 1 or 0 muscle function.

DISCUSSION

The overall goal of this study was to provide specific information on the extent of spontaneous recovery of upper extremity function after cervical SCI. We specifically focused on changes from six to 12 months post-injury. This recovery is relevant in the context of nerve transfer surgery to improve upper extremity function. In SCI, nerve transfer surgery has been more successful when undertaken before 12 months following injury [15, 16]; this time sensitivity seems to be similar to that seen in peripheral nerve injury.

Surgical restoration of motor function

Nerve transfer surgery can restore elbow extension, wrist extension and hand opening and closing [2, 3, 5]. An expendable donor nerve with intact UMN control is transected and coapted to a non-functional recipient nerve. After transfer, the donor nerve regenerates through the recipient nerve to restore muscle function. An ideal donor nerve is relatively expendable, close to the recipient neuromuscular target, similar in caliber to the recipient, and has synergistic muscle action [17]. A single donor nerve to one muscle may restore function to several neuromuscular recipients [17]. A donor with even as little as 20% of the recipient nerve's motor neuron count may successfully restore function [18]. Thus, nerve transfers have less biomechanical and physiologic limitations than tendon transfers.

After cervical SCI, potential expendable donor nerves include the nerves to the posterior/middle deltoid (C5), brachialis (C5) and supinator (C5) [3, 15, 19, 20]; the use of nerves to brachioradialis (C6) [19], extensor carpi radialis brevis (C6) [19], and teres minor (C5) [20] has also been described. These donor nerves are transferred to recipient nerve branches to the wrist extensor (C6), triceps (C7), and/or finger and thumb extensors (C7/C8) or flexors (C8/T1).

Outcomes after nerve transfer in people with SCI are comparable to those reported after tendon transfer [15, 19, 21, 22]. Overall, the donor site deficits are minimal [21, 23]; however, sometimes, no functional gains occur after nerve transfer [22]. Many factors influence outcomes but results seem improved when individuals undergo surgery soon after injury [15]. A recent publication showed excellent gains across a variety of outcomes measures, including muscle strength, pinch, grip and validated functional tests and surveys, after nerve transfer in SCI [3].

Implications of spontaneous recovery of motor function for surgical treatment options

In this study, we found that most individuals without elbow extension (C7) and hand closing (C8/T1) function at 6 months, did not regain this function at 12 months post-cervical SCI.

Thus, the overall rehabilitation plan should include early evaluation, including electrodiagnostic testing where applicable, and consideration of nerve transfer surgery to restore these functions before the window of opportunity closes. People with SCI want information about treatment options [24]; this work provides evidenced-based surgically-relevant data on recovery to inform that discussion.

Unlike tendon transfers, which can be performed in eligible candidates at any time point after injury [1], nerve transfers are often time-sensitive. The target recipient myotomes often undergo motor degeneration due to direct injury to the lower motor neuron at the zone of SCI [4]. Our previous study found that pre-operative electrodiagnostic testing can predict the degree of recipient motor degeneration [25]. This motor degeneration is present in the majority of recipient muscles [5, 6] and these individuals with SCI lose the opportunity to undergo nerve transfer if too much time elapses. While we published a case report that suggests that late nerve transfer (>10 years post-SCI) can lead to gains in function, this case was an unusual exception [26]. Unfortunately, it seems that in most cases nerve transfers may fail if not done soon after injury.

By contrast, many limbs do spontaneously recover antigravity wrist extension (C6) between 6 and 12 months after SCI. Unfortunately there are limited surgical treatment options to restore wrist extension using tendon transfers, particularly if brachioradialis function is absent. Although anatomic studies suggest that options to restore this important function exist [27], there is only one successful clinical case report of using a nerve transfer to restore wrist extension in SCI [28]. Similarly, many limbs without T1 function spontaneously recover partial function between 6 and 12 months post-SCI. Attempted nerve transfer to restore intrinsic muscle function in SCI was not successful in a single case report [2]. Thus, nerve transfers to restore wrist extension and intrinsic function deserve additional investigation before widespread adoption.

The EMSCI database did not include information about spontaneous recovery of thumb and finger extension (C8/T1). Therefore, we cannot specifically comment on the relative advantages of doing an early nerve transfer of the donor nerve to supinator (C5) to posterior interosseous nerve (C8/T1) to restore thumb and finger extension and thumb abduction.

In addition, it seems feasible to consider using weaker donor nerves for early nerve transfer surgery. This is based on the observation that at 6 months after cervical SCI, the majority of individuals starting with grade 3 C5 muscle function by 12 months spontaneously recover to grade 4 or 5. Future prospective assessment of outcomes will clarify if early antigravity-only (grade 3) muscle function in C5 donor nerves at 6 months can successfully be used to restore recipient nerve function without compromising donor site function.

Finally, additional work should be done to compare nerve to tendon transfer [3, 29] and on combining these treatment strategies where appropriate [30].

Implications of factors that influence spontaneous recovery on nerve transfer surgery

Numerous factors may affect the extent of motor recovery, including timing and adequacy of spine decompression and stabilization surgery [31], severity (completeness) of cord injury [7, 8, 12, 13], medical complications following injury [32], trajectory of recovery [33], and age [34].

Recovery in incomplete SCI is more substantial and more variable [9, 12]. Similar to previous studies, our study showed greater recovery after motor-incomplete cervical SCI (AIS C, D) than motor-complete cervical injury (AIS A, B); further work is needed to assess the role for nerve transfer in incomplete SCI.

Finally, there is great variability in how changes in strength translate to gains in the ability to perform activities of daily living, independence or participation [35]. However, this is beyond the scope of this study.

Surgical decision-making

There are a number of individual factors and preferences that might affect the decision to undergo nerve transfer early after injury [36, 37]. In a few reported cases, where the recipient LMN is preserved, a nerve transfer may successfully restore UMN control and function even years (>10) post-SCI [26]. Similarly, tendon transfers may present a late surgical option for functional restoration, provided there are adequate donor tendons for transfer. The EMSCI database records ISNCSCI, which does not provide detailed information about muscles available for tendon transfer. Thus we are unable to determine tendon transfer options in the EMSCI cohort.

As stated above, recent work suggests that electrodiagnostic testing can accurately determine the extent of preserved LMN function [25]. Individuals with preserved LMN identified by electrodiagnostic studies could choose to undergo nerve transfer surgery later when spontaneous recovery has plateaued. However, the current evidence indicates that nerve transfer outcomes in SCI are superior if performed within 12 months after SCI injury [15].

Limitations

Database studies have inherent limitations. The sample size was limited by the data available in the EMSCI database. At 6 months post-SCI, there were 268 participants with mid-cervical SCI, which should have provided data for 536 limbs. However, due missing data at the 12 months follow-up, only 449 limbs were included for analysis. It is possible that those who were retained in the database had less recovery and thereafter returned for follow-up care and testing more than those who were lost to follow-up, which would lead to selection bias. Also, the data presented in our study did not evaluate spontaneous recovery after 12 months; although others have shown that recovery is limited at these later times [38]. Finally, grading spinal cord segments by manual muscle testing can be unreliable. Future work might prospectively monitor recovery and use additional data such as results from serial imaging or other testing to better predict what function returns or does not return in each individual person/limb, but this was outside of the scope of the current work.

CONCLUSION

Because nerve transfer surgery appears to be time sensitive, it is imperative for people with SCI and their healthcare providers to have accurate and detailed information about the pattern and timeline of spontaneous recovery. Our study found that for the majority of individuals there was limited spontaneous motor recovery between 6 and 12 months after cervical motor-complete SCI. In this context, individuals *without* (grade 0, 1, 2*)* elbow extension and hand function should undergo early clinical evaluation and electrodiagnostic testing to determine if the recipient LMN is intact. Those with intact LMN may be candidates for delayed nerve transfer with or without tendon transfer surgery and rehabilitation to gain movement. However, if the LMN is *not* intact, the information from our study can be used to help make informed choices about early (within 6 month of SCI) nerve transfer surgery.

DATA AVAILABILITY

The dataset generated and/or analysed during the current study is available from the corresponding author.

REFERENCES

1. Hentz VR, Leclercq C. Surgical rehabilitation of the upper limb in tetraplegia. London, England: W.B. Saunders; 2002.
2. Hill EJR, Fox IK. Current best peripheral nerve transfers for spinal cord injury. Plast Reconstr Surg. 2019;143:184e–198e.
3. van Zyl N, Hill B, Cooper C, Hahn J, Galea MP. Expanding traditional tendon-based techniques with nerve transfers for the restoration of upper limb function in tetraplegia: A prospective case series. Lancet 2019;394:565–75.
4. Coulet B, Allieu Y, Chammas M. Injured metamere and functional surgery of the tetraplegic upper limb. Hand Clin. 2002;18:399–412.
5. 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 2018;10:1173–84e1172.
6. Berger MJ, Robinson L, Krauss EM. Lower motor neuron abnormality in chronic cervical spinal cord injury: Implications for nerve transfer surgery. J Neurotrauma. 2022;39:259–65.
7. Fu SY, Gordon T. Contributing factors to poor functional recovery after delayed nerve repair: Prolonged denervation. J Neurosci. 1995;15:3886–95.
8. Waters RL, Adkins RH, Yakura JS, Sie I. Motor and sensory recovery following complete tetraplegia. Arch Phys Med Rehabil. 1993;74:242–7.
9. Waters RL, Adkins RH, Yakura JS, Sie I. Motor and sensory recovery following incomplete tetraplegia. Arch Phys Med Rehabil. 1994;75:306–11.
10. Raineteau O, Schwab ME. Plasticity of motor systems after incomplete spinal cord injury. Nat Rev Neurosci. 2001;2:263–73.
11. Curt A, Van Hedel HJ, Klaus D, Dietz V, Group, SS E-. Recovery from a spinal cord injury: Significance of compensation, neural plasticity, and repair. J Neurotrauma. 2008;25:677–85.
12. Ditunno JF Jr., Cohen ME, Hauck WW, Jackson AB, Sipski ML. Recovery of upper-extremity strength in complete and incomplete tetraplegia: A multicenter study. Arch Phys Med Rehabil. 2000;81:389–93.
13. Steeves JD, Kramer JK, Fawcett JW, Cragg J, Lammertse DP, Blight AR, et al. Extent of spontaneous motor recovery after traumatic cervical sensorimotor complete spinal cord injury. Spinal Cord. 2011;49:257–65.
14. Kirshblum SC, Biering-Sorensen F, Betz R, Burns S, Donovan W, Graves DE, et al. International standards for neurological classification of spinal cord injury: Cases with classification challenges. J Spinal Cord Med 2014;37:120–7.
15. Cain SA, Gohritz A, Friden J, van Zyl N. Review of upper extremity nerve transfer in cervical spinal cord injury. J Brachial Plex Peripher Nerve Inj. 2015;10:e34–e42.
16. Kobayashi J, Mackinnon SE, Watanabe O, Ball DJ, Gu XM, Hunter DA, et al. The effect of duration of muscle denervation on functional recovery in the rat model. Muscle Nerve. 1997;20:858–66.
17. Mackinnon SE, Novak CB. Nerve transfers. New options for reconstruction following nerve injury. Hand Clin. 1999;15:643–66.
18. Gordon T, Yang JF, Ayer K, Stein RB, Tyreman N. Recovery potential of muscle after partial denervation: A comparison between rats and humans. Brain Res Bull. 1993;30:477–82.
19. Bertelli JA, Ghizoni MF. Nerve transfers for restoration of finger flexion in patients with tetraplegia. J Neurosurg Spine. 2017;26:55–61.
20. Bertelli JA, Ghizoni MF. Nerve transfers for elbow and finger extension reconstruction in midcervical spinal cord injuries. J Neurosurg. 2015;122:121–7.
21. Khalifeh JM, Dibble CF, Van Voorhis A, Doering M, Boyer MI, Mahan MA, et al. Nerve transfers in the upper extremity following cervical spinal cord injury. Part 2: Preliminary results of a prospective clinical trial. J Neurosurg Spine. 2019;31:641–53.
22. Khalifeh JM, Dibble CF, Van Voorhis A, Doering M, Boyer MI, Mahan MA, et al. Nerve transfers in the upper extremity following cervical spinal cord injury. Part 1: Systematic review of the literature. J Neurosurg Spine. 2019;31:629–40.

23. 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). 2015;10:60–7.
24. L'Hotta AJ, James AS, Curtin CM, Kennedy C, Kenney D, Tam K, et al. Surgery to Restore Upper Extremity Function in Tetraplegia—Preferences for Early and Frequent Access to Information. PM&R: The Journal of Injury, Function and Rehabilitation. Accepted for publication. https://doi.org/10.1002/pmrj.12862.
25. Jain NS, Hill EJR, Zaidman CM, Novak CB, Hunter DA, Juknis N, et al. Evaluation for late nerve transfer surgery in spinal cord injury: Predicting the degree of lower motor neuron injury. J Hand Surg Am. 2020;45:95–103.
26. Fox IK, Novak CB, Kahn LC, Mackinnon SE, Ruvinskaya R, Juknis N. Using nerve transfer to restore prehension and grasp 12 years following spinal cord injury: a case report. Spinal Cord Ser Cases. 2018;4:37.
27. Ziaziaris WA, Ahadi MS, Gill AJ, Ledgard JP. The anatomy of nerve transfers used in tetraplegic hand reconstruction. J Hand Surg Am. 2021, advance online publication. https://doi.org/10.1016/j.jhsa.2021.09.003.
28. Friden J, Gohritz A. Brachialis-to-extensor carpi radialis longus selective nerve transfer to restore wrist extension in tetraplegia: Case report. J Hand Surg Am. 2012;37:1606–8.
29. 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. 2018;24:275–87.
30. 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. 2019;29:521–30.
31. Grassner L, Wutte C, Klein B, Mach O, Riesner S, Panzer S, et al. Early Decompression (<8 h) after traumatic cervical spinal cord injury improves functional outcome as assessed by spinal cord independence measure after one year. J Neurotrauma. 2016;33:1658–66.
32. Denis AR, Feldman D, Thompson C, Mac-Thiong JM. Prediction of functional recovery six months following traumatic spinal cord injury during acute care hospitalization. J Spinal Cord Med. 2018;41:309–17.
33. Jaja BNR, Badhiwala J, Guest J, Harrop J, Shaffrey C, Boakye M, et al. Trajectory-based classification of recovery in sensorimotor complete traumatic cervical spinal cord injury. Neurology. 2021; 96:e2736–48.
34. Wilson JR, Davis AM, Kulkarni AV, Kiss A, Frankowski RF, Grossman RG, et al. Defining age-related differences in outcome after traumatic spinal cord injury: analysis of a combined, multicenter dataset. The spine journal: Official journal of the North American Spine. Society 2014;14:1192–8.
35. Whiteneck G, Meade MA, Dijkers M, Tate DG, Bushnik T, Forchheimer MB. Environmental factors and their role in participation and life satisfaction after spinal cord injury. Arch Phys Med Rehabilitation. 2004;85:1793–803.
36. Mooney A, Hewitt AE, Hahn J. Nothing to lose: A phenomenological study of upper limb nerve transfer surgery for individuals with tetraplegia. Disabil Rehabil. 2021;43:3748–56.
37. Fox I, Hoben G, Komaie G, Novak C, Hamm R, Kahn L, et al. Nerve transfer surgery in cervical spinal cord injury: A qualitative study exploring surgical and caregiver participant experiences. Disabil Rehabilitation. 2021;43:1542–9.
38. Kirshblum S, Millis S, McKinley W, Tulsky D. Late neurologic recovery after traumatic spinal cord injury. Arch Phys Med Rehabil. 2004;85:1811–7.

ACKNOWLEDGEMENTS

Amanda Miller, MD provided advice on clinically relevant information.

AUTHOR CONTRIBUTIONS

JD was responsible for study design, extracting and analyzing the data, interpreting the results and writing the report. JDS was responsible for study design, interpreting the results and editing the report. AC was responsible for interpreting the results and providing feedback on the report. MM was responsible for extracting and analyzing the data, and providing feedback on the report. CBN was responsible for study design and providing feedback on the report. IKF was responsible for study design, interpreting the results and writing the report. CC, CK, DO and KCS were responsible for study design and providing feedback on the report. DO, RA, NW, RR, JV, JB and YBK were responsible for data collection and providing feedback on the report.

FUNDING

This work was supported by the Department of Defense-W81XWH-17-1-0285 Supporting Patient Decisions about Upper-Extremity Surgery in Cervical SCI (PI: Ida K. Fox). The contents of this work do not represent the views of the U.S. Department of Veterans Affairs or the United States Government.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41393-022-00834-6.

Correspondence and requests for materials should be addressed to Ida K. Fox.

DOD CONSORTIUM

Catherine Curtin[8], Carie Kennedy[6], Doug Ota[8] and Katherine C. Stenson[7,9]

[8]Palo Alto Veterans Healthcare System, Palo Alto, California, USA. [9]Division of Physical Medicine and Rehabilitation, Washington University School of Medicine, St. Louis, MO Missouri, USA

EMSCI CONSORTIUM

Doris Maier[10], Rainer Abel[11], Norbert Weidner[12], Rüdiger Rupp[12], Joan Vidal[13], Jesús Benito[13] and Yorck-Bernhard Kalke[14]

[10]BG-Trauma Center, Murnau, Germany. [11]Hohe Warte Bayreuth, Bayreuth, Germany. [12]Spinal Cord Injury Center, Heidelberg University Hospital, Heidelberg, Germany. [13]Institute Guttmann, Neurorehabilitation Hospital, Barcelona, Spain. [14]RKU Universitäts- und Rehabilitationskliniken Ulm, Ulm, Germany.