ISCoS The International Spinal Cord Society

www.nature.com/scsandc

ARTICLE

Check for updates

Donor activation focused rehabilitation approach to hand closing nerve transfer surgery in individuals with cervical level spinal cord injury

Lorna C. Kahn[1]✉, Adam G. Evans[2,3], Elspeth J. R. Hill[3] and Ida K. Fox[3]

STUDY DESIGN: Case Series.
OBJECTIVES: To describe the donor activation focused rehabilitation approach (DAFRA) in the setting of the hand closing nerve transfers in cervical spinal cord injury (SCI) so that therapists may apply it to treatment of individuals undergoing this procedure.
SETTING: United States of America—Academic Level 1 Trauma Center.
METHODS: We reviewed the records of individuals with cervical SCI who underwent nerve transfer to restore hand closing and post-surgery DAFRA therapy at our institution. The three post-surgery phases of DAFRA included (1) early phase (0–12 months) education, limb preparation, and donor activation exercises, (2) middle phase (12–24 months) volitional recipient muscle activation and (3) late phase (18 + months) strengthening and incorporation of motion in activities of daily living.
RESULTS: Subtle gains in hand closing were first observed at a mean of 8.4 months after hand closing nerve transfer surgery. Remarkable improvements including discontinuation of assistive devices, independence with feeding and urinary function, and measurable grip were observed. Function continued to improve slowly for one to two more years.
CONCLUSIONS: A deliberate, slow-paced (monthly for >2 years post-surgery) and incremental therapy program—DAFRA—can be used to improve outcomes after nerve transfer to restore hand closing in cervical SCI.
SPONSORSHIP: This work was made possible by funding from the Craig H. Neilsen Foundation Spinal Cord Injury Research on the Translation Spectrum (SCIRTS) Grant: Nerve Transfers to Restore Hand Function in Cervical Spinal Cord Injury (PI: Ida Fox).

Spinal Cord Series and Cases (2022)8:47 ; https://doi.org/10.1038/s41394-022-00512-y

INTRODUCTION

Nerve transfers are a novel method to restore thumb and finger flexion—hand closing—in mid-cervical spinal cord injury (SCI). Most importantly, they can help expand the treatment options for individuals with more caudal patterns of injury who are *not* candidates for traditional tendon transfer surgery. The hand closing nerve transfer enhances tenodesis (passive grip force), reduces the need for adaptive equipment and enables some individuals to maintain hand control regardless of wrist position.

The past decade has seen increasing interest in nerve transfers as a novel therapeutic option to improve hand function in people with spinal cord injury (SCI) [1–18] Nerve transfers do not require extended periods of non-weight bearing or long-term changes to wheelchair transfer techniques, which may deter individuals from seeking tendon transfer surgeries [19]. The transfer re-routes an expendable donor under volitional control to a recipient that is not working because of the intervening SCI.

The nerve transfer from the donor musculocutaneous nerve (brachialis muscle branch) to branches of the recipient median nerve has been used to restore hand closing in people with SCI [20–22]. In addition to reinnervating flexor pollicis longus (FPL) and the flexor digitorum profundus of the index finger (FDPi) via the anterior interosseous nerve (AIN), additional branches to flexor digitorum superficialis (FDS) and/or flexor carpi radialis (FCR) may be included as recipients to enhance grasp function. The nerve transfer is performed proximal to the elbow, requiring axons to grow 12–18 cm at approximately 1 mm per day to reach the recipient motor end plates and restore function [2, 23, 24].

This is in contrast to the nerve transfer of supinator to posterior interosseous nerve, which has been used to successfully restore *hand opening* function. This hand opening surgery and its post-operative therapy have been previously described [25]. Surgical techniques for the *hand closing* nerve transfer have been previously described but the results have been mixed [1–3, 26]. We believe this is in part due to the critical role of a long duration, donor focused, motor re-education therapy program. The donor activation focused rehabilitation approach (DAFRA) is a strategy for rehabilitation after a nerve transfer originally developed for brachial plexus and peripheral nerve injury populations to maximize functional outcomes [27]. It recognizes the altered neural pathways created by nerve transfers and attempts to strengthen these pathways through patient education, cortical

[1]Milliken Hand Rehabilitation Center, Department of Occupational Therapy, Washington University, St. Louis, MO 63110, United States. [2]School of Medicine, Meharry Medical College, Nashville, TN 37208, United States. [3]Division of Plastic and Reconstructive Surgery, Washington University School of Medicine, St. Louis, MO 63110, United States. ✉email: kahn.lorna.c@wustl.edu

Received: 30 July 2020 Revised: 11 April 2022 Accepted: 13 April 2022
Published online: 29 April 2022

plasticity and exercise. We believe DAFRA also has an essential role in improving outcomes in people with cervical SCI who have had nerve transfers, particularly for transfers with a greater regeneration distance from donor to recipient muscle where the recovery time is protracted.

The purpose of this case series is to describe the application of DAFRA to individuals with SCI who underwent both nerve transfer surgery and therapy to restore hand closing.

METHODS

Overview

We retrospectively reviewed the therapy and medical records of individuals with cervical level SCI who underwent nerve transfer surgery *and* therapy at our center from August 2013 to August 2018 and had at least 18 months of follow-up. One individual (L.C.K.) provided all post-operative therapy adapting the use of DAFRA to this population. During this time, our routine clinical care included a comprehensive upper extremity exam and DAFRA therapy with variable collection of the Graded and Refined Assessment of Strength, Sensibility, and Prehension (GRASSP) outcome measures [28]. Available data and subjectively reported outcomes information were collected and summarized. Specifically, we reviewed information about the gains in movement (results of manual muscles testing) over time, time to gain in movement, and self-reported gains in function (this included ability to do new activities of daily living, changes in use of electronics, assistive devices and subjective report of gains in strength).

Summary of the post-operative rehabilitation program

The DAFRA used in our practice consisted of 3 phases: early, middle, and late; Table 1. Early phase therapy included education, limb preparation, and donor activation exercises. Manual muscle testing of FDPi and FPL was performed at each therapy session to capture the first volitional contraction [29]. This was the moment when the first sign of reinnervation was established. Middle phase therapy began when trace recipient muscle contraction was noted and, for this hand closing nerve transfer, focused on elbow flexion co-contraction with assisted thumb and finger flexion. Late phase therapy began when 3/5 recipient strength was attained. Use of resistance tools and customized functional activities were incorporated into the program.

Early phase rehabilitation

The goals of early phase therapy were to prepare the limb for recovery of function and to educate about relevant anatomy, physiology and DAFRA concepts. Adequate understanding of the donor/recipient neuromuscular relationships and the importance of using donor activation to gain recipient function were essential to this program.

After 2 weeks of post-operative rest, individuals met with a certified hand/physical therapist. A baseline evaluation of edema, scar, residual joint contracture, and strength of donor (elbow flexors) and recipient (hand closing) muscles was performed. Compression sleeves and reduced limb exertion were recommended to manage edema if present. Thickened or adherent scars were treated with scar massage.

Both flexion and extension contractures of the fingers are seen in cervical SCI. Some degree of interphalangeal joint flexion contractures and extrinsic flexor muscle tightness is useful for holding objects, however, excess flexion from contracture or muscle shortness in the fingers limits thumb contact during lateral pinch and grasp of larger objects. Thus, contractures were treated with passive ROM (PROM) exercises and static progressive or dynamic finger-based extension orthoses. This was especially important as reinnervation occurred during later phases; increased flexor tone would exacerbate flexion contractures. Extension contractures were addressed with PROM exercises, flexion gloves and Ace wraps.

Motor re-education began with the introduction of donor activation exercises. Due to the altered innervation pattern following a nerve transfer control of the recipient muscles was initially activated with co-contraction of the donor elbow flexors. For this hand closing nerve transfer, a substantial emphasis was placed on frequent elbow flexion exercises—termed “firing the donor.” Individuals were instructed to perform 10 repetitions of active elbow flexion with the forearm pronated (to maximize activation of the nerve to the brachialis versus the biceps muscle) every hour throughout the day. Expectations were set for these donor activation exercises to continue well beyond the first year.

The second exercise component combines active (donor) elbow flexion with passive finger and thumb flexion to introduce the concept of co-contraction of donor and recipient muscles. It was designed to develop neuroplasticity by strengthening the donor and recipient neuromuscular connection on a cortical level [30–32]. During the early phase, when there is no recipient function, individuals were instructed to flex the elbow with effort while visualizing the hand closing into a fist. If an aide or family member was available to assist with home exercise the therapist instructed this person to passively flex the thumb and fingers while the person with SCI actively flexed the elbow. This ‘patterning’ activity provided neuronal activation that may have enhanced neural regeneration [33].

Elbow flexion exercises were advanced during this early phase by adding resistance with weights or bands. Use of a grip wrap device such as Active Hand Grip Wrap (Active Hands Company, Solihull, UK) provided the passive positioning of the fingers and thumb in flexion to hold the band or weight. **(**Fig. 1**)** An Ace wrap or a home-made device was also used. These devices eliminated the need for an assistant to perform the passive thumb and finger flexion component of the exercises and facilitated independent donor activation and donor/recipient co-contraction exercises.

Isometric elbow flexion (in forearm pronation to activate the brachialis donor and not the biceps) exercises were also used. The elbow was actively flexed with the forearm blocked by a table, the contralateral limb, or the arm of the wheelchair. Individuals were encouraged to perform some form of these resisted elbow flexion with passive hand closing exercises 2–4 times per day.

When available, the BTE Primus Simulator (Baltimore Therapeutic Equipment Co., Hannover, MD, USA) was used. This combined tool simulation with computerized tracking and visual feedback. Initially, subjects required a grip assist device to hold the tools, but as flexor tone increased during middle and late phases, their ability to hold tools improved and many could manage some tools without the device. Ideal tools are those which required simultaneous grip and elbow flexion (i.e., lever #802). The BTE tracked gains in strength with immediate feedback that many found motivational. Such devices were not necessary, but creative programs that improved participation and provide motivation by incorporating objects such as a hammer or steering wheel may have augmented recovery.

Weekly visits were recommended for those with joint contractures until they demonstrated understanding of the home exercise program (HEP). Otherwise, monthly visits were used to assess passive and active ROM. The therapist demonstrated and performed a variety of manually and/or mechanically resisted elbow flexion exercises with and without passive hand closing to reinforce the motor re-education program.

Recovery of hand closing was assessed during early phase therapy visits. Recipient muscle (FDS, FPL and FDPi) reinnervation was checked by positioning the wrist in neutral and holding the finger or thumb in extension while resisting elbow flexion in forearm pronation. Flexor tone and active motion were assessed with the elbow in flexion and extension to appreciate any early change due to donor activation. The wrist was blocked to prevent contributions from tenodesis.; Supplementary information video 1.

Middle phase rehabilitation

The first appearance of volitional movement in a recipient muscle marked the beginning of the middle phase of rehabilitation. The goal of this phase was to establish volitional control of hand closing. Early on subjects may have been unaware of progressive motor recovery, which presented as subtly increased flexor muscle tone and/or augmented tenodesis function. Motor control of the recovering thumb and finger flexor muscles was enhanced by functional hand closing activities. Therapeutic interventions in this phase included use of built-up handles on functional objects that have the shape and size to enable successful pinch and grip activities with incomplete flexion. Items such as foam cylinders, cones and theraputty were used to promote grip while the therapist provided manually resisted elbow flexion.

Frequent, short bouts of isolated thumb and/or finger flexion with resisted elbow flexion were performed; ideally 5-10 repetitions, several times per day. Some formal exercises were replaced by functional activities of daily living (ADLs) that included combined hand closing activity with concomitant elbow flexion. Self-feeding without an assistive device was a common goal for many people thus creating a program that involved retrieving, holding, and bringing a food item to the mouth was a useful example.

Muscle fatigue was a hallmark of newly reinnervated muscles. Individuals were advised to “respect fatigue” by limiting recipient muscle activity when fatigue was evident. This was achieved by encouraging a high frequency of low repetition exercises throughout the day and during

Table 1. Guidelines for rehabilitation following hand closing nerve transfers in cervical SCI.

TIMELINE (timeline can be variable)	ASSESSMENT	EDUCATION	IN PERSON TREATMENT	HOME PROGRAM
EARLY PHASE 1 MONTH	• Baseline motor evaluation of elbow flexors, FDP, (FDS) and FPL strength • Baseline grasp and pinch function with validated measure kit (i.e., GRASSP) or with cones and marbles if kits are unavailable • Assess for MP/IPJ contractures	• Identify pertinent anatomy; 'donor' and 'recipient' muscles and their functions • Describe general concepts of motor re-education • Emphasize protracted timeline for recovery of function	• Weekly visits • Address contractures with PROM and orthoses • Edema and scar management prn	• Elevation/rest x 2 weeks post-surgery • Scar management • "donor activation" exercises (active elbow flexion in forearm pronation) hourly x10+ repetitions
EARLY PHASE 2–6 MONTHS	• Hand suppleness • Flexor tone (early sign of recipient muscle recovery) • recipient function • donor strength	• Recommend grip assist device such as Activehand™ to aid with resistance exercises and encourage flexor tone if it is lacking	• Monthly visits • Address contractures prn • Resisted elbow flexion with visualized and passive finger/thumb flexion • BTE™ tool simulator (when available) with grip assist device	• Donor activation exercises hourly x10+ repetitions • Resisted elbow flexion with isometrics, resistance bands or weights • Patterning donor and recipient activation by visualizing finger/thumb flexion with elbow flexion
MIDDLE PHASE 8–18 MONTHS (once a volitional movement is observed)	• Measure distance of flexed index finger to DPC • Measure degrees of isolated thumb flexion • Measure functional grasp and pinch to capture change /progress with GRASSP, etc.	• Demonstrate control of new volitional movement with resisted elbow flexion to increase recipient muscle response during grasp/pinch activities	• Weekly-monthly visits, dependent on need or individual preference • Repetitive functional grasping with isometric or resisted elbow flexion • Prehension activities with foam cylinders, objects wrapped in theraputty • BTE™ tool #802/lever for donor/recipient exercise; gradually wean grip assist device as tone and strength increase	• Donor activation exercises, hourly • Use hand for ADL's with emphasis on strong co-contraction of elbow flexors • Add foam tubing to utensils/devices to improve grasp w/o assistive device • Attach HandHelper™ type gripper (w/ single rubber band) to a secured resistance band for combined grip with resisted elbow flexion exercise
LATE PHASE 12–24+ MONTHS (once full volitional flexion is observed)	• Measure functional grasp and pinch to capture change/progress with GRASSP, etc.	• Challenge the individuals to incorporate activities that require resistance to general use of the hand • function will continue to improve for several years if challenged with compliance to HEP	• Weekly-monthly visits, dependent on need • BTE™ tools are now used without a grip aid • Digit flexion using pinch clips, theraputty (pinch/pull, retrieving buried marbles, grasping and pulling dowels through the putty), and retrieving and holding weighted spheres and cones • Once grip is adequate to hold weight introduce resisted eccentric wrist extension to gain functional grip without tenodesis • Provide manual resistance to elbow flexion during eccentric phase (as elbow straightens) while maintaining grip to train the arm to maintain grip with reaching, separating donor and recipient functions	• Continue resisted elbow flexion as part of daily routine; this may include a resistance band with a foam tube hand attached to the WC • Theraputty exercises • Light gripper such as Hand Helper™ • Individual-specific functional activities to improve ADL's (holding water bottles, hairbrush, pen/pencil, cooking utensil)

Abbreviations: *FDP*-flexor digitorum profundus, *FDS*-flexor digitorum superficialis, *FPL*-flexor pollicis longus, *GRASSP*-Graded and Refined Assessment of Strength, Sensibility and Prehension outcome measure, *MPJ*-metacarpal-phalangeal joint, *IPJ*-interphalangeal joint, *PROM*-passive range of motion, *BTE*- Baltimore Therapeutic Equipment Primus Stimulator combined tool simulation device, DPC-distal palmar crease, *ADL's*-activities of daily living, *WC*-wheelchair, *HEP*-home exercise program

Fig. 1 Grip aid devices are helpful during Early Phase Rehabilitation. A grip aid device such as Active Hand Grip Wrap (Active Hands Company, Solihull, UK) enables individuals to hold resistance tubing or a hand weight with the involved hand in flexion and perform resisted donor activation (elbow flexion) exercises independently.

therapy sessions. Initially, 5 repetitions may be all that is capable of the weak, reinnervated muscle. Typically, muscle fatigue decreased gradually as muscle reinnervation continued and strength improved.

During this phase some individuals benefitted from orthoses to position the thumb and index finger for more successful pinch. A hand-based thumb opposition orthosis (with the IP joint free) supported the hypermobile thumb, improved opposition to the index finger, and allowed for isolated thumb IP joint flexion exercises. Those with excess index finger flexion posturing were given a finger-based extension orthosis, such as a prefabricated Oval 8™, to improve index finger positioning for lateral pinch against the thumb.

Frequency of therapy visits during the middle phase was ideally 2-4 times per month.

Late phase rehabilitation

The late phase of therapy was initiated once the person demonstrated full, active flexion in the thumb and fingers. The hallmark of this phase was the introduction of resistance exercises and strengthening of the recipient muscles.

Theraputty, pinch clips, and weighted cones or spheres were used to encourage pinch and grip with increased resistance. **(**Fig. 2**) (**Supplementary info. 2).

Resisted donor muscle activation continued to play a role in maximizing recipient muscle performance during this late phase and was incorporated in the activity or manually applied by the therapist to increase the strength of finger and thumb flexion contractions. For example, a Hand Helper™ (grip strength device) was outfitted with a resistance band attached to a doorknob to advance co-contraction exercises of hand closing with elbow flexion. (Fig. 3) Ultimately, some individuals performed resisted hammer curls with a foam handle attached to the resistance band, as demonstrated in (Supplementary info. 3).

Individuals were challenged to incorporate activities that required active grasp into their daily routine. Utensils and toothbrushes were used to gain strength and confidence in self-care without an assistive device. Work or hobby-related tasks were also incorporated into the program.

The ability to hold and manipulate light objects with the wrist flexed was a useful goal that enhanced hand function. As volitional grip strength improved reliance on tenodesis wrist extension to maintain grip decreased. The ability to grasp and place items with the wrist neutral or flexed equated with improved control and less dropping of grasped items. For this reason, wrist extension eccentrics were introduced to strengthen finger flexion when the wrist was lowered out of end-range extension. An example of the wrist extension curl set-up is shown in (Supplementary info. 4). Training for this began with a hand wrap to assist grip and was removed as strength improved. It was not uncommon for this to take two or more years to achieve.

Ideal frequency of treatment during the late phase was 2-4 times per month until individuals demonstrated a clear understanding how to

Fig. 2 Resistance is introduced during Late Phase Rehabilitation. During late phase therapy, weighted spheres may be used for strengthening the finger and thumb flexor muscles and improving functional strength.

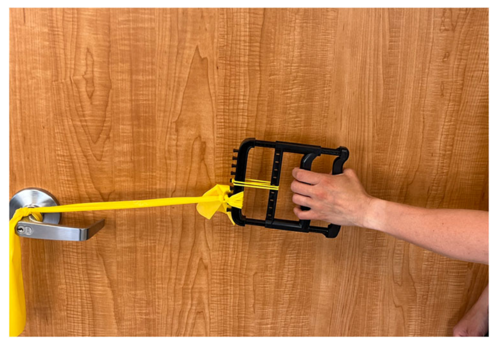

Fig. 3 Combined resisted donor and recipient muscle exercises are introduced in the Late Phase Rehabilitation. During late phase therapy, combining use of a hand exerciser with an exercise band attached to a doorknob enables one to practice combined resisted recipient finger flexion with resisted elbow flexion for strengthening at home.

perform active finger and thumb flexion activities and their home exercise program. At a minimum, monthly visits were used to guide incorporation of new activities as strength, endurance and abilities improved.

RESULTS

Nine males had both surgery and therapy at our institution and met criteria for inclusion in this case series. Demographic and surgery information are provided, Table 2. Post-operative follow-up averaged 40 months (range: 18.5-86). One had a 9-month unscheduled gap in therapy during which time their new function appeared, and another reported no change in function. There was missing GRASSP data for two.

Volitional trace movement of recipient musculature most often appeared between 6 and 10 months post-surgery and required strong co-contraction of elbow flexors. At that point, the subtle change was often not recognizable to the individual.

Our subjects' mean operative hand total GRASSP score improved by 15.7 (standard deviation 9.7) points above the pre-operative mean total GRASSP score of 40.7 (standard deviation 10.7) points. Eight subjects had gains in hand closing function. Measurable grip was present in four of the subjects. Four reported discontinuance of assistive devices for eating at an average of 12 months post-operatively. Three mentioned new independence with self-catheterization at an average of 14.5 months post-surgery. Finally, six described new ability to hold bottles or cups at an average of 16 months post-surgery (Tables 2, 3).

DISCUSSION

Therapy is critical to care of the upper extremity cervical SCI [34] and, particularly, to improving outcomes in the setting of novel nerve transfer surgery to restore hand closing function in cervical SCI. There is little in the literature about rehabilitation after nerve transfer surgery, [35] particularly in the setting of SCI [25]. The hand-closing nerve transfer in SCI has unique challenges that affect outcomes. This case series allowed us to provide preliminary guidelines about education, timing, frequency, and exercises that may improve outcomes; future work should incorporate these suggestions and the collection of formal, outcomes measures that are applicable to this unique population.

It is crucial that everyone (the individual with SCI, caregivers, and therapist) appreciates the deliberately slow pace of this rehabilitation protocol, have realistic expectations about the incremental gains in function and long timeline of recovery, and appropriately schedule the frequency and duration of therapy. Multiple factors, including the long-distance from coaptation to recipient muscle, contribute to gains in function that are obtained over years after surgery [36]. Indeed others have also suggested that results after nerve transfer and repair do continue to improve for years after surgery [37].

We recommend therapy for a minimum of once a month for >2 years post-surgery. This is considerably different from the current practices for rehabilitation following tendon transfers in the tetraplegic population where therapeutic intervention is often complete within 5 months following surgery [38]. One challenge to the protracted rehabilitation after nerve transfer, is to maintain motivation; it may take up to 10 months or more before new function is noted in the recipient muscle. The subtle appearance of volitional movement can be difficult to appreciate. Monthly therapy visits enable the therapist to identify the earliest sign of motor recovery and appropriately adjust the therapy regimen to strengthen the newly innervated muscle. Creating and recursively modifying a home program that reflects the individual's interests and goals is imperative to success.

Pairing movements that incorporate resisted donor (elbow flexion) and recipient (hand closing) muscle activation remains a dominant theme throughout as functional activities are woven through the program. Simplifying the home program with realistic options for resisting donor activation with hand closing tasks that are meaningful to the individual can be helpful—for example, weight-lifting using small hand held weights to do biceps curls. Functional gains develop slowly throughout the second year and monthly visits can be adequate to provide input regarding advancements to their programs.

The individuals in our series saw substantial improvements in function as assessed by total GRASSP score. Compared to other spontaneous recovery studies reporting GRASSP score improvements in people with SCI [39, 40], the observed increase in our population is notable and clinically significant [41]. In this population, hand closing can improve to the day-to-day self-reported gains in functional independence despite the lack of measurable grip strength achieved by over half of the individuals.

There are many limitations to our case series. The same therapist provided therapy and assessed outcomes, providing a potential source of bias. Future studies should include a prospective data collection that better captures the exercises that improve achievable participant goals. They should also incorporate the rigorous collection of outcomes measures such as the International Standards for Neurological Classification of SCI (ISNCSCI), International Classification for Surgery of the Hand in Tetraplegia (ICSHT) [42], Spinal Cord Independence Measure III (SCIM-III), and the Canadian Occupational Performance Measure

Table 2. Patient demographics, preoperative assessment, and surgery.

Subject	Race	Age at Time of Surgery	Years from Injury to Surgery	Injury Etiology	GRASSP (L, R)	Ipsilateral Preoperative Strength			Recipient of Brachialis Nerve (Side)	Supinator to PIN Transfer Done
						Elbow Extension	Elbow Flexion	Wrist Extension		
1	White	48	0.6	MVC	39, 37	2-	5	5	(L) AIN, FCR	No
2	White	29	12.7	MVC	NT	0	4	3	(R) AIN, FCR	No
3	White	35	12.6	ATV	36, 46	5	5	5	(R) AIN, FDS	No
4	White	31	10.4	Motorcycle	44, 25	2-	4	2-	(R) AIN, FCR	Yes
5	White	23	1.7	Sports - Diving	47, 42	2-	5	2	(R) AIN	Yes
6	White	22	1.1	ATV	20, 15	2	5	5	(L) AIN, FDS, FCR	No
7	White	34	11.4	Sports - Diving	58, 50	0	5	4-	(R) AIN/FDS/FCR (mixed)	Yes
8	White	22	13.1	MVC	51, 34	0	5	4	(L) AIN, FDS	No
9	Black	21	4.5	MVC	35, 56	3+	5	3-	(L) AIN, mixed FDS/FCR	Yes

GRASSP Graded Redefined Assessment of Strength, Sensibility, and Prehension. *L* Left. *R* Right. *MVC* Motor Vehicle Crash. *ATV* All-Terrain Vehicle. *AIN* Anterior Interosseous Nerve (innervates flexor pollicis longus and flexor digitorum profundus to index finger). *FDS* Flexor Digitorum Superficialis. *FCR* Flexor Carpi Radialis. *FDP* Flexor Digitorum Profundus. *PIN* Posterior Interosseous Nerve (innervates thumb and finger extensors).

Table 3. Outcomes after Surgery.

Subject	Months to first FDPi flicker	Months to first FPL flicker	Months to first new function*	Grip strength at postoperative follow-up	Postoperative ipsilateral GRASSP score (net change) at postoperative follow-up	Reported functional changes & clinical observations
1	5.4	7.3	12.4	Slightly moved needle at 20.8 months	47 (+8) at 26.2 months	• Move pegs in a peg board • Hold eating utensils without assistive device • Hold a driving bar without a device • Does not need clip device to insert catheter • Better hold on ophthalmoscope at work • Undress upper body clothing including unbuttoning • Augmented tenodesis • Pinch 0.91 kg clip
2	9.1	15.8	N/A	None	NT	No new function, no loss of function
3	7.9	7.9	9.9	0.91 kg at 20.4 months	64 (+18) at 30 months	Discontinued all assistive devices for utensils and toothbrush, • Hold a water bottle • Improved pinch to eat chips • Self-catheterization is easier and faster and can be done without clips • Grips with 0.91 kg and pinches with 0.34 kg w/o splint • Holds and pours with forearm pronated • Drinks one-handed from water bottle • Grabs ping-pong balls and marbles • Zips zippers • Unwraps cheese, does light cooking, picks up ham and cheese slices to make sandwich, holds cups • Eats nachos without making a mess, picks up tic-tacs • Moves heavy items like pots • Takes medications without any assistance
4	5.8	5.8	5.8	None	NT	• Self-catheterizes independently • Lifts a full 355 mL can • "can pick up anything"; before surgery couldn't pick up anything • Uses the right hand to self-feed • Use a remote control, can move small pegs
5	8.1	8.1	6.3	Slightly moved needle at 24.1 months	44 (+19) at 14 months	• Fine motor function has improved gradually • Picks up small items • Releases objects easier • Pulls a gun trigger of < 1.59 kg • Holds onto a piece of paper • Holds a can but with trouble bringing it to the mouth due to losing WE with pronation • Hangs onto things a little better like a fork or phone or near empty drinking glass • Able to lean over side of chair to grasp fallen objects • Built a model catapult • Throws a ball for the dog • Reaches into a bag like potato chips or pocket much more easily due to being able to hold wrist straighter

Table 3. continued

Subject	Months to first FDPi flicker	Months to first FPL flicker	Months to first new function*	Grip strength at postoperative follow-up	Postoperative ipsilateral GRASSP score (net change) at postoperative follow-up	Reported functional changes & clinical observations
6	9.1	9.1	8.8	2.73 kg at 22.8 months	53 (+33) at 15 months	• Opens doors better although some difficulty opening the hand to hold around the door handle • Eating is better • Able to brush teeth one-handed • Types at computer using thumb • Self-catheterizes independently now • Picks up phone with outstretched arm, • Slightly increased grip that augments ability to hold bottle, can, or phone • Picks up golf tees, wood pegs, fries
7	9.7	9.7	9.7	None	58 (+8) at 24 months	• More strength in the right side with increased grip • Writes better • Picks up a dollar bill • Controls the right fist without activating the donor • Easier to grab a drink/cup/water bottle • Picks up phone better • Holds a pen • Holds/throws ball for dog • Eats with the right hand using built up handle
8	6.4	6.4	6.4	None	56 (+5) at 25 months	• 1.14 kg measurable grasp • Stopped using bent utensils for cuff splint and occasionally uses a built-up handle for soft food, • Pincer grasp; moves marbles, wooden pegs, golf tees, and holds dixie cups • Holds balls and buttons • Grasps narrower dowel rods
9	6.2	6.2	Pause in Follow-up	None	46 (+11) at 17 months	• Holds objects in palm including water bottle

*New function was subjectively determined by the subject as meaningful function arising after the nerve transfer, examples of which are listed in the column titled *Reported Functional Changes & Clinical Observations*.
FDPi Index Finger Flexor Digitorum Profundus. *FPL* Flexor Pollicis Longus. *GRASSP* Graded Redefined Assessment of Strength, Sensibility, and Prehension. *N/A* Not Applicable. *NT* Not Tested.

COPM) and other validated outcomes scales [43, 44]. Future work should also consider the identification and/or development of simplified outcomes measures that can be tracked by therapists, other clinicians, and the person living with SCI to clearly show the gains that are achievable with these surgical interventions and comprehensive long-term DAFRA therapy.

CONCLUSION

Supervised rehabilitation with a therapist familiar with the concepts of DAFRA should continue through the second post-operative year to maximize outcomes after nerve transfers to restore hand closing function in individuals with cervical SCI.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

REFERENCES

1. 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. PMR 2018;10:1173–84.e2.
2. Bertelli JA, Ghizoni MF. Nerve transfers for restoration of finger flexion in patients with tetraplegia. J Neurosurg Spine. 2017;26:55–61.
3. Fox IK. Nerve transfers in tetraplegia. Hand Clin. 2016;32:227–42.
4. 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. 2015;136:780–92.
5. 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. 2015;10:60–7.
6. 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. 2015;10:e34–e42.
7. Bertelli JA, Ghizoni MF. Nerve transfers for elbow and finger extension reconstruction in midcervical spinal cord injuries. J Neurosurg. 2015;122:121–7.
8. van Zyl N, Hahn JB, Cooper CA, Weymouth MD, Flood SJ, Galea MP. Upper limb reinnervation in C6 tetraplegia using a triple nerve transfer: case report. J Hand Surg. 2014;39:1779–83.
9. Senjaya F, Midha R. Nerve transfer strategies for spinal cord injury. World Neurosurg. 2013;80:e319–e26.
10. Fridén J, Gohritz A. Muscle and nerve transfer in tetraplegia. J Neurosurg. 2013;118:706–7.
11. Bertelli JA, Mendes Lehm VL, Tacca CP, Winkelmann Duarte EC, Ghizoni MF, Duarte H. Transfer of the distal terminal motor branch of the extensor carpi radialis brevis to the nerve of the flexor pollicis longus: an anatomic study and clinical application in a tetraplegic patient. Neurosurgery 2012;70:1011–6.
12. Bertelli JA, Tacca CP, Winkelmann Duarte EC, Ghizoni MF, Duarte H. Transfer of axillary nerve branches to reconstruct elbow extension in tetraplegics: a laboratory investigation of surgical feasibility. Microsurgery 2011;31:376–81.
13. Bertelli JA, Ghizoni MF, Tacca CP. Transfer of the teres minor motor branch for triceps reinnervation in tetraplegia. J Neurosurg. 2011;114:1457–60.
14. Oppenheim JS, Spitzer DE, Winfree CJ. Spinal cord bypass surgery using peripheral nerve transfers: review of translational studies and a case report on its use following complete spinal cord injury in a human. Experimental article. Neurosurg Focus. 2009;26:E6–E.
15. 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. 2013;38:1366–9.
16. Mackinnon SE, Yee A, Ray WZ. Nerve transfers for the restoration of hand function after spinal cord injury. J Neurosurg. 2012;117:176–85.
17. Fridén J, Gohritz A. Brachialis-to-extensor carpi radialis longus selective nerve transfer to restore wrist extension in tetraplegia: case report. J Hand Surg. 2012;37:1606–8.
18. Bertelli JA, Tacca CP, Ghizoni MF, Kechele PR, Santos MA. Transfer of supinator motor branches to the posterior interosseous nerve to reconstruct thumb and finger extension in tetraplegia: case report. J hand Surg. 2010;35:1647–51.
19. 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 Rehabil. 2019:1–8.
20. Palazzi S, Palazzi J-L, Caceres J-P. Neurotization with the brachialis muscle motor nerve. Microsurgery 2006;26:330–3.
21. Hill EJR, Fox IK. Current best peripheral nerve transfers for spinal cord injury. Plast Reconstruct Surg. 2019;143:184e–98e.
22. Bendersky M, Bianchi HF. Double innervation of the brachialis muscle: anatomic-physiological study. Surg Radio Anat. 2012;34:865–70.
23. Yang F, Zhang X, Xie X, Yang S, Xu Y, Xie P. Intramuscular nerve distribution patterns of anterior forearm muscles in children: a guide for botulinum toxin injection. Am J Transl Res. 2016;8:5485–93.
24. Menorca RMG, Fussell TS, Elfar JC. Nerve physiology: mechanisms of injury and recovery. Hand Clin. 2013;29:317–30.
25. Hahn J, Cooper C, Flood S, Weymouth M, van Zyl N. Rehabilitation of supinator nerve to posterior interosseous nerve transfer in individuals with tetraplegia. Arch Phys Med Rehabil. 2016;97:S160–8. 6 Suppl
26. 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 rehabilitation. 2018;24:275–87.
27. Kahn LC, Moore AM. Donor activation focused rehabilitation approach: maximizing outcomes after nerve transfers. Hand Clin. 2016;32:263–77.
28. Kalsi-Ryan S, Beaton D, Curt A, Duff S, Popovic MR, Rudhe C, et al. The graded redefined assessment of strength sensibility and prehension: reliability and validity. J Neurotrauma. 2012;29:905–14.
29. Cuthbert SC, Goodheart GJ Jr. On the reliability and validity of manual muscle testing: a literature review. Chiropr Osteopat. 2007;15:4.
30. Malessy MJA, Bakker D, Dekker AJ, Van Duk JG, Thomeer RTWM. Functional magnetic resonance imaging and control over the biceps muscle after intercostal-musculocutaneous nerve transfer. J Neurosurg. 2003;98:261–8.
31. Anastakis DJ, Malessy MJA, Chen R, Davis KD, Mikulis D. Cortical plasticity following nerve transfer in the upper extremity. Hand Clin. 2008;24:425–vii.
32. Dayan E, Cohen LG. Neuroplasticity subserving motor skill learning. Neuron 2011;72:443–54.
33. Udina E, Puigdemasa A, Navarro X. Passive and active exercise improve regeneration and muscle reinnervation after peripheral nerve injury in the rat. Muscle Nerve. 2011;43:500–9.
34. Johanson ME. Rehabilitation after surgical reconstruction to restore function to the upper limb in tetraplegia: a changing landscape. Arch Phys Med Rehabil. 2016;97:S71–4. 6 Suppl
35. Kahn LC, Moore AM. Donor activation focused rehabilitation approach: Maximizing outcomes after nerve transfers. Hand Clin. 2016;32:263–77.
36. 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.
37. Wang JP, Rancy SK, Lee SK, Feinberg JH, Wolfe SW. Shoulder and elbow recovery at 2 and 11 years following brachial plexus reconstruction. J Hand Surg Am. 2016;41:173–9.
38. Moutet F, Corcella D, Forli A, Bouyer M, Aribert M, Giot JP. General principles of tendon transfers: The ten commandments. Hand Surg Rehabil. 2021.
39. Jung JH, Lee HJ, Cho DY, Lim J-E, Lee BS, Kwon SH, et al. Effects of combined upper limb robotic therapy in patients with tetraplegic spinal cord injury. Ann Rehabil Med. 2019;43:445–57.
40. Inanici F, Samejima S, Gad P, Edgerton VR, Hofstetter CP, Moritz CT. Transcutaneous electrical spinal stimulation promotes long-term recovery of upper extremity function in chronic tetraplegia. IEEE Trans Neural Syst Rehabil Eng. 2018;26:1272–8.
41. Kalsi-Ryan S, Beaton D, Curt A, Popovic MR, Verrier MC, Fehlings MG. Outcome of the upper limb in cervical spinal cord injury: Profiles of recovery and insights for clinical studies. J Spinal Cord Med. 2014;37:503–10.
42. McDowell CL, Moberg E, House JH. The second international conference on surgical rehabilitation of the upper limb in tetraplegia (quadriplegia). J Hand Surg. 1986;11:604–8.
43. Itzkovich M, Shefler H, Front L, Gur-Pollack R, Elkayam K, Bluvshtein V, et al. SCIM III (Spinal Cord Independence Measure version III): reliability of assessment by interview and comparison with assessment by observation. Spinal Cord. 2018;56:46–51.
44. Toomey M, Nicholson D, Carswell A. The clinical utility of the Canadian Occupational Performance Measure. Can J Occup Ther. 1995;62:242–9.

ACKNOWLEDGEMENTS

We thank Allison L'Hotta for her review and thoughtful insights and Carie Kennedy, BSN, RN for her assistance with data collection. This work was made possible by funding from the Craig H. Neilsen Foundation Spinal Cord Injury Research on the Translation Spectrum (SCIRTS) Grant: Nerve Transfers to Restore Hand Function in Cervical Spinal Cord Injury (PI: Ida Fox).

AUTHOR CONTRIBUTIONS

LK was responsible for data collection, first draft of manuscript, table creation and subsequent manuscript edits. AE was responsible for data collection and analysis, table creation and subsequent manuscript edits. EH contributed to manuscript edits. IF contributed to data analysis, crafted the discussion section and contributed to multiple subsequent edits.

COMPETING INTERESTS

The authors declare no competing interests.

ETHICS APPROVAL

All applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during this research.

ADDITIONAL INFORMATION

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41394-022-00512-y.

Correspondence and requests for materials should be addressed to Lorna C. Kahn.

Reprints and permission information is available at http://www.nature.com/reprints