Expanding traditional tendon-based techniques with nerve transfers for the restoration of upper limb function in tetraplegia: a prospective case series

Natasha van Zyl, Bridget Hill, Catherine Cooper, Jodie Hahn, Mary P Galea

Summary
Background Loss of upper extremity function after cervical spinal cord injury greatly affects independence, including social, vocational, and community engagement. Nerve transfer surgery offers an exciting new option for the reanimation of upper limb function in tetraplegia. The aim of this study was to evaluate the outcomes of nerve transfer surgery used for the reanimation of upper limb function in tetraplegia.

Methods In this prospective case series, we consecutively recruited people of any age with early (<18 months post-injury) cervical spinal cord injury of motor level C5 and below, who had been referred to a single centre for upper extremity reanimation and were deemed suitable for nerve transfer. All participants underwent single or multiple nerve transfers in one or both upper limbs, sometimes combined with tendon transfers, for restoration of elbow extension, grasp, pinch, and hand opening. Participants were assessed at 12 months and 24 months post-surgery. Primary outcome measures were the action research arm test (ARAT), grasp release test (GRT), and spinal cord independence measure (SCIM).

Findings Between April 14, 2014, and Nov 22, 2018, we recruited 16 participants (27 limbs) with traumatic spinal cord injury, among whom 59 nerve transfers were done. In ten participants (12 limbs), nerve transfers were combined with tendon transfers. 24-month follow-up data were unavailable for three patients (five limbs). At 24 months, significant improvements from baseline in median ARAT total score (34·0 [IQR 24·0–38·3] at 24 months vs 16·5 [12·0–22·0] at baseline, p<0·0001) and GRT total score (125·2 [65·1–154·4] vs 35·0 [21·0–52·3], p<0·0001) were observed. Mean total SCIM score and mobility in the room and toilet SCIM score improved by more than the minimal detectable change and the minimal clinically important difference, and the mean self-care SCIM score improved by more than the minimal detectable change between baseline and 24 months. Median Medical Research Council strength grades were 3 (IQR 2–3) for triceps and 4 (IQR 4–4) for digital extensor muscles after 24 months. Mean grasp strength at 24 months was 3·2 kg (SD 1·5) in participants who underwent distal nerve transfers (n=5), 2·8 kg (3·2) in those who had proximal nerve transfers (n=9), and 3·9 kg (2·4) in those who had tendon transfers (n=8). There were six adverse events related to the surgery, none of which had any ongoing functional consequences.

Interpretation Early nerve transfer surgery is a safe and effective addition to surgical techniques for upper limb reanimation in tetraplegia. Nerve transfers can lead to significant functional improvement and can be successfully combined with tendon transfers to maximise functional benefits.

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Introduction Cervical spinal cord injury is a devastating, life-changing injury, which can affect anyone at any time. Each year, 230000–500000 people worldwide acquire a spinal cord injury, with more than 50% of these injuries resulting in tetraplegia.1 Tetraplegia affects almost every aspect of a person’s work, family, and social life. For people living with tetraplegia, improvement in hand function is the highest-ranked goal.2 Reconstruction of upper extremity function is a crucial component of the management of people with mid-level or low-level cervical spinal cord injury, as it has the capacity to restore important functions such as elbow extension, wrist extension, grasp, key pinch, and release. Traditionally, these functions have been reconstructed by use of tendon transfers, which move the tendon of a functioning muscle to a new insertion site to recreate the function of a paralysed muscle.3

The success of nerve transfers in the treatment of brachial plexus and peripheral nerve injury has inspired interest in nerve transfers for people with spinal cord injury.4 Nerve transfers are an attractive surgical option because they allow direct reanimation of the muscle anatomically and biomechanically designed to do that function. Nerve transfers can reanimate more than one muscle at a time—in contrast to tendon transfers, which usually require one tendon to reconstruct one function—and multiple nerve transfers can be completed simultaneously.4 Nerve transfers require a smaller
operative incision and a substantially shorter immobilisation or splinting time post-surgery. In addition, nerve transfers avoid the technical challenges of tendon transfer surgery (intraoperative tendon tensioning) and mechanical failure post-surgery (tendon rupture, adhesion, or stretch). As nerve transfers can use different donors, the options for reconstruction and the total number of functions that can be restored is increased when combined with tendon transfers. In this study, we aimed to evaluate the clinical and functional outcomes of nerve transfer surgery used for reanimation of upper limb function in eligible patients with tetraplegia and to compare these with published outcomes for tendon transfer surgery.

Methods
Study design and participants
We did a prospective case series with 2-year follow-up, reported in accordance with the PROCESS guidelines. We recruited people with early (<18 months post-injury) cervical spinal cord injury who had been consecutively referred to a single centre for upper extremity reanimation in Melbourne, Australia. Participants of any age were included if they had confirmed tetraplegia with a preoperative motor level of injury of C5 or below, deemed suitable for nerve transfer surgery by the surgical team, were able to provide informed consent, and were able to comply with postoperative protocols. People with a confirmed peripheral nerve injury in the limb planned for surgery, a decreased passive range of motion across a joint planned for reanimation, a pre-existing neurological condition, or an acquired brain injury were excluded. People with non-traumatic spinal cord injury were not specifically excluded; however, because our unit serves predominantly a post-trauma population, the study sample included only patients with traumatic spinal cord injury. This study is registered with the Australian and New Zealand Clinical Trials Registry (number ACTRN1261500179538). Ethics approval was obtained from the Austin Health Human Research Ethics Committee (approval number HREC/13/Austin/245), and all participants provided written, informed consent.

Intervention
All participants underwent single or multiple nerve transfers in one or both upper limbs. The following nerve transfers were done: for elbow extension, transfer of the nerve supplying the teres minor muscle, or the motor portion of the posterior axillary nerve, or both, to the nerve supplying the triceps muscle. (B) Transfer to restore hand opening, from the nerve supplying the supinator muscle to the posterior interosseous nerve. (C) Transfer to restore grasp and pinch, from the nerve supplying the extensor carpi radialis brevis muscle to the anterior interosseous nerve.

Figure 1: Schematic representations of nerve transfers
(A) Transfer to restore elbow extension, from the nerve supplying the teres minor muscle to the nerve supplying the triceps muscle. (B) Transfer to restore hand opening, from the nerve supplying the supinator muscle to the posterior interosseous nerve. (C) Transfer to restore grasp and pinch, from the nerve supplying the extensor carpi radialis brevis muscle to the anterior interosseous nerve.
A  Transfer of nerve supplying teres minor to nerve supplying triceps

B  Transfer of nerve supplying supinator to posterior interosseous nerve (anterior approach)

C  Transfer of nerve supplying extensor carpi radialis brevis to anterior interosseous nerve

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Donor nerve transection site
Recipient nerve transection site
Motor nerve
Sensory nerve
Quadrangular space
Site of nerve coaptation

Stage 1
Nerve supplying extensor carpi radialis brevis muscle
Superficial branch of radial nerve
Anterior interosseous nerve

Stage 2
Radial nerve
Biceps tendon
Posterior interosseous nerve

Stage 3
Radial nerve
Biceps tendon
Posterior interosseous nerve

Stage 4
Nerve supplying supinator muscle
Radial nerve
Posterior interosseous nerve

Finished graft
Superficial branch of radial nerve
Radial nerve
Posterior interosseous nerve
triceps (figure 1A); for finger and thumb extension (to allow hand opening), transfer of the nerve supplying the supinator muscle to the posterior interosseous nerve (figure 1B); and for thumb, index finger, and middle finger flexion (to allow grasp and pinch), transfer of the nerves supplying the extensor carpi radialis brevis muscle (figure 1C), the brachialis muscle, or the supinator muscle to the anterior interosseous nerve. In one case, the nerve supplying the brachialis muscle was transferred to the nerve supplying the flexor digitorum superficialis muscle to reconstruct flexion of the fingers. Although the primary aim of the study was to examine outcomes for nerve transfer surgery, some participants had standard tendon transfers to restore grasp or pinch in one hand and nerve transfers for grasp or pinch in the other hand to provide two different styles of hand functionality. In three limbs (International Classification for Surgery of the Hand in Tetraplegia [ICSHT] group 1), wrist extension was restored with a brachioradialis to extensor carpi radialis brevis tendon transfer.

All three surgeons were highly experienced grade 4 specialists in upper limb reconstruction and nerve transfer surgery. All surgeries were done with the patient supine and under general anaesthesia, with a single dose of muscle relaxant and a thromboprophylactic agent administered on induction. Patients wore compression stockings and used calf compression devices. An arm tourniquet was not used. After dissection and identification with use of a nerve stimulator and locator device (Checkpoint Stimulator/Locator, Checkpoint Surgical, Cleveland, OH, USA), nerves were divided and transferred, and then coapted under 10× magnification with microsurgical technique using interrupted 9·0 nylon and a fibrin sealant (TISSEEL, Baxter, Deerfield, IL, USA).

The operated limb(s) were protected in a sling for 1–2 weeks to safeguard the coaptation site. If nerve transfer surgery was combined with tendon transfer

<table>
<thead>
<tr>
<th>Injury classification</th>
<th>Surgical procedures</th>
<th>MRC grade at 24 months post-surgery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Triceps</td>
</tr>
<tr>
<td>SNLI AIS Motor level†</td>
<td>Nerve transfers for elbow extension</td>
<td>Nerve transfers for grasp, pinch, or hand opening</td>
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<tr>
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<td>C2 A C7 5</td>
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<tr>
<td>Participant 3</td>
<td>C5 B C5 2</td>
<td>TM-triceps</td>
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<tr>
<td>Left side</td>
<td>C5 B C6 4</td>
<td>–</td>
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<tr>
<td>Participant 4</td>
<td>C4 A C6 2</td>
<td>TM-triceps, mPAA-triceps</td>
</tr>
<tr>
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<tr>
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<td>Left side</td>
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<td>TM-triceps, mPAA-triceps</td>
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<tr>
<td>Participant 6 (right side)</td>
<td>C4 A C6 4</td>
<td>TM-triceps, mPAA-triceps</td>
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</table>
| Participant 7 (right side) | C4 A C6 1 | mPAA-triceps | Supinator-PIN | Brachioradialis-FDP | 2 | 4 | 2 | 2 | 1 | 3† | NA | NA | (Table 2 continues on next page)
### Table 2: Spinal injury classification, surgical procedure, and strength outcomes at 24 months

<table>
<thead>
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<th>Injury classification</th>
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<th>MRC grade at 24 months post-surgery</th>
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<td>Nerve transfers</td>
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<td>Transfers for grasp, pinch, or wrist extension</td>
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<td>3 4 4 3 2 4 3 NA</td>
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<td>brachialis-AIN</td>
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<tr>
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<td>2 4 3 3 2 4†§ 4† NA</td>
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<td>Supinator-AIN</td>
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<td>Supinator-PIN</td>
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<tr>
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<td>Supinator-PIN,</td>
<td>LFU LFU LUF LUF LUF LUF LUF LUF</td>
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<tr>
<td>mPAx-triceps</td>
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<tr>
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<td>Supinator-PIN</td>
<td>LUF LUF LUF LUF LUF LUF LUF LUF</td>
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<td>ECRB-AIN</td>
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Surgical procedures are shown as donor-recipient; for nerve transfers, the muscle names listed refer to the muscles innervated by the nerves used in the procedure. MRC=Medical Research Council. SNLI=single neurological level of injury (measured at a mean of 11 weeks post-spinal cord injury). AIS=American Spinal Injury Association impairment scale. ICSHT=International Classification for Surgery of the Hand in Tetraplegia. EDC=extensor digitorum communis. EPL=extensor pollicis longus. APL=abductor pollicis longus. ECU=extensor carpi ulnaris. FDP=flexor digitorum profundus. FDS=flexor digitorum superficialis. PIN=posterior interosseous nerve. AIN=anterior interosseous nerve. NA=not applicable. ECRL=extensor carpi radialis longus. LFU=lost to follow-up. FPL split=transfer of 50% of the FPL tendon to EPL. mPAx=motor portion of posterior axillary nerve. ECRB=extensor carpi radialis brevis. *Motor level measured at time of surgery. †MRC grade reported from the digit with the best power. §Anomalous slip of FPL-to-FDP index.
surgery, the regimen for immobilisation defaulted to that for tendon transfer surgery. After immobilisation, intensive therapy was provided to maintain joint mobility and to practise activation of the donor muscle function paired with passive recipient muscle movement. When reanimation of the recipient muscle(s) was first detected, recipient strengthening was commenced through the patient activating donor muscle movement against resistance. All post-surgical therapy was done in an outpatient setting, unless the participant was still an inpatient (seven of 16 patients) for routine post-spinal cord injury rehabilitation.

**Outcome assessment**

Spinal injury levels were classified according to the International Standards for Neurological Classification of Spinal Cord Injury, including the American Spinal Injury Association impairment scale (AIS) and the ICSHT. The same independent assessor did assessments preoperatively and at 12 months and 24 months post-surgery. Strength was graded on the Medical Research Council (MRC) scale for muscle strength. MRC grades for finger flexion and extension were based on the digit with the best power. Grasp and pinch were measured with standard dynamometers (Jamar Plus Digital Hand Dynamometer, Lafayette Instrument Company, Lafayette, IN, USA; and a baseline mechanical pinch gauge [opening 5 mm]. Fabrication Enterprises, White Plains, NY, USA). At each assessment, participants were positioned so that they were unable to lever against the assessor or use a tenodesis grasp (a passive grasp or pinch enabled by active wrist extension). First webspace opening, sensation, proprioception, and pain were also recorded using standard procedures. Activity was assessed with three primary outcome measures: the action research arm test (ARAT), the grasp release test (GRT), and the spinal cord independence measure (SCIM). Two secondary outcome measures of activity were also used: the Canadian Occupational Performance Measure (COPM) and satisfaction with the outcome of each individual nerve transfer (three statements, each rated on a five-point Likert scale). The assessments used in this study and the timepoints at which they were done are outlined in the appendix (p 1).

All adverse events and serious adverse events were monitored and recorded.

**Data management and analysis**

Assessments were recorded on individual case report forms and data were managed with the Research Electronic Data Capture tool, hosted at The Florey Institute of Neuroscience and Mental Health. Mean and SD (if data were normally distributed) or median and IQR (if data were skewed) were reported for each outcome measure. A Wilcoxon signed-rank test was used to assess the differences between pre-surgical and post-surgical ARAT, GRT, and COPM scores, as well as webspace opening. The threshold for significance was set at p<0·05. Spearman’s rank-order correlation coefficients were calculated to assess relationships between measures, with correlations considered weak if r_s<0·30, moderate if r_s≥0·30 and r_s<0·50, and strong if r_s≥0·50. All data were analysed with use of SPSS version 19.

**Role of the funding source**

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

**Results**

Between April 14, 2014, and Nov 22, 2018, 16 participants (13 male and three female) with traumatic spinal cord
injury were recruited (table 1). Motor vehicle accidents accounted for five (31%) injuries, with the remainder caused by falls, sports, or diving. The single neurological level of injury (SNLI), measured a mean 11 weeks post-spinal cord injury, ranged from C2 to C7, and all participants had motor complete injuries. All participants had recovered to a motor level of C5–C7 before surgery, with an ICSHTF grouping of 1–5 (table 2). The mean time to surgery was 10 months post-injury (range 5–15). Two participants were lost to follow-up and one death (unrelated to the surgery) occurred before the 12-month follow-up assessment.

All nerve and tendon transfer surgeries done, spinal injury classifications, and strength outcomes at 24 months for each participant are shown in table 2. Among the 13 participants (22 limbs) who completed 24-month follow-up, the following surgeries were done: 15 transfers of the nerve supplying the teres minor muscle or the motor portion of the posterior axillary nerve (or both) to the nerve supplying the triceps; 21 transfers of the nerve supplying the supinator muscle to the posterior interosseous nerve; 13 transfers of the nerves supplying the brachialis muscle, the extensor carpi radialis brevis muscle, or the supinator muscle to the anterior interosseous nerve; and one transfer of the nerve supplying the brachialis muscle to the nerve supplying the flexor digitorum superficialis muscle. Function after a triple nerve transfer to restore elbow extension, grasp, pinch, and hand opening in a single limb is shown in video 1. Eight of the 13 participants (nine limbs) had tendon transfers, including seven brachioradialis to flexor pollicis longus, five extensor carpi radialis longus to flexor digitorum profundus, one brachioradialis to flexor digitorum profundus, and one brachioradialis to extensor carpi radialis brevis.

MRC grades for recipient muscles at the 24-month follow-up assessment are presented in table 3. Results for nerve transfers to the anterior interosseous nerve to restore grasp and pinch are subdivided into proximal transfers (nerve supplying the brachialis muscle, which arises more proximally in the limb and further from the recipient or target muscle) and distal transfers (nerve supplying the extensor carpi radialis brevis muscle or the supinator muscle, which are closer to target). No participant was able to obtain a score on the grasp or pinch dynamometers before surgery. Participants who underwent tendon transfers for grasp and pinch achieved greater power on average for both grasp and pinch than did participants who underwent nerve transfers, with distal nerve transfers resulting in better performance than proximal transfers (table 4). There was a statistically significant difference in webspace opening between baseline and 24 months (p=0·0019; table 5, appendix p 2). Webspace opening was greater in participants who received only nerve transfers for grasp and pinch (median 110·0 mm [IQR 90·0–120·0]) than in those who also received tendon transfers for grasp and pinch (92·5 mm [76·3–107·5]; Mann-Whitney p=0·41; appendix p 2).

Median ARAT and GRT total scores increased significantly between baseline and 24-month follow-up (table 5, appendix p 2). In addition, all participants had improved by more than the minimal detectable change and the minimal clinically important difference for the total SCIM score and the mobility in the room and toilet subcategory (table 6), and by more than the minimal detectable change for the self-care subcategory at 24 months. COPM performance and COPM satisfaction scores also significantly improved, and the changes in scores were greater than the two-point clinically important change at 24 months (table 5).

At 24 months, satisfaction with surgery was highest in patients who received a transfer of the nerve supplying the supinator muscle to the posterior interosseous nerve; for 14 (70%) of 20 surgeries for which responses were available, patients reported that they agreed with the
statement “I am satisfied with the outcome”. Among those patients, satisfaction with hand opening was higher among the subgroup who received nerve transfers for grasp and pinch on the same hand as the transfer of the nerve supplying the supinator muscle to the posterior interosseous nerve (nine [75%] of 12 surgeries) than among those who underwent tendon transfers on the same hand (five [63%] of eight). Satisfaction with nerve transfers for grasp and pinch was reported for seven (58%) of 12 surgeries for which responses were available, with four (33%) neutral responses and one (8%) dissatisfied response. Satisfaction with triceps reconstruction was reported for six (43%) of 14 surgeries, with five (36%) neutral and three (21%) dissatisfied responses. No participant regretted having the surgery, and all stated that they would have it again and recommend it to others.

Strong positive correlations were found between the ARAT, GRT, COPM performance, and SCIM self-care scores (appendix p 3). Lateral pinch was strongly correlated with ARAT total score ($r_s=0.64$) and GRT total score ($r_s=0.63$), and grasp with GRT total score ($r_s=0.67$). Satisfaction with release correlated strongly with webspace opening ($r_s=-0.72$) and digital extension strength ($r_s=0.52$). Satisfaction with triceps surgery correlated strongly with triceps strength ($r_s=-0.76$), and satisfaction with grasp and pinch correlated moderately with the grip strength ($r_s=0.41$), lateral pinch ($r_s=0.44$), and webspace ($r_s=0.46$).

No participants experienced an increase in musculoskeletal or neuropathic pain. Nine participants reported musculoskeletal pain involving primarily the shoulders and upper thoracic spine before the surgery, six of whom still had this pain at 24 months post-surgery. Four participants reported neuropathic pain primarily in the hands and forearms at baseline testing. Of these, two reported no change, one reported that his pain resolved between 12 months and 18 months post-surgery, and one noted a marked decrease in pain over the 2-year follow-up period.

Four (8%) of the 50 nerve transfers with 24-month follow-up failed completely (MRC grade 0 or 1): two transfers of the nerve supplying the teres minor muscle and the motor portion of the posterior axillary nerve to the nerve supplying the triceps (both in participant 5), one transfer of the nerve supplying the brachialis to the anterior interosseous nerve (participant 4), and one transfer of the nerve supplying the supinator muscle to the posterior interosseous nerve (participant 14). These participants all had an SNLI of C4 and AIS category A on admission to rehabilitation.

Two participants experienced a temporary partial decrease in their wrist extension strength after a transfer of the nerve supplying the supinator muscle to the posterior interosseous nerve (participants 7 and 16), which had fully recovered by the 12-month review. Two participants experienced alteration in sensation: one to the dorsum of the thumb after a transfer of the nerve supplying the supinator muscle to the posterior interosseous nerve (participant 8), and another to the skin supplied by the posterior cutaneous nerve of the arm after a transfer of the nerve supplying the teres minor muscle and the motor portion of the posterior axillary nerve to the nerve supplying the triceps muscle (participant 5). Neither loss affected day-to-day use of the hand or limb. Post-surgical loss of proprioception to the metacarpophalangeal and distal interphalangeal joints of the index finger was recorded in two participants.
(participants 6 and 14). Neither was aware of these changes. There were no minor complications of surgery, including haematoma, seroma, infection, or wound dehiscence. At 12-month follow-up, there were no reductions in donor movement power as synergist muscles had been left intact.

25 adverse events (including urinary tract infection), and five serious adverse events (including a fall from a wheelchair with femur fracture) unrelated to the surgery were recorded in the patient cohort during the 24-month follow-up period. None of the six adverse events related to the surgery had any ongoing functional consequences. Adverse events are summarised in the appendix (p 4).

Discussion
This project is the first to comprehensively examine outcomes for early, multiple nerve transfer surgery in the upper limbs of people with tetraplegia following traumatic spinal cord injury, and is the largest prospective series of nerve transfers reported in this population to date. An additional unique aspect of this study is the combining of nerve transfers for grasp and pinch reconstruction in one hand with tendon transfers in the contralateral hand.

18 nerve transfers to the triceps for elbow extension (15 with completed follow-up) were done in our study. Elbow extension assists in many activities, including reaching above the head, transfer of position (eg from lying to sitting, or from bed to wheelchair), wheelchair propulsion, and extending the arm out to increase available workspace. The choice of donor nerve—the nerve supplying the teres minor muscle, the motor portion of the posterior axillary nerve, or both—was determined by intraoperative nerve stimulation, with the motor portion of the posterior axillary nerve being included if stimulation of the nerve supplying the teres minor muscle was suboptimal. In this study, changes in score on the SCIM mobility (room and toilet) subscale could largely be attributed to the restoration of triceps function allowing for enhanced wheelchair or commode propulsion and transfer capacity. The median MRC grade for elbow extension for the whole cohort was 3, which is similar to that previously reported for tendon transfer. The short immobilisation times necessary following nerve transfers (10 days in a sling), versus the 6–12 weeks in a brace needed for tendon transfers, make nerve transfers for elbow extension an attractive option.

Grasp and pinch are key actions allowing independence in many activities of daily living, including self-feeding, writing, picking up heavy objects, self-catheterisation, and wheelchair use. In this study, grasp strength, pinch strength, and ARAT and GRT scores showed significant improvements at 24-month follow-up in hands reconstructed with either nerve or tendon transfers (figure 2A, video 2). Mean pinch strength at 24 months following tendon transfers (1·9 kg) was similar to that reported in the literature (2 kg), and greater than that achieved by distal nerve transfers in our study (1·5 kg). Grasp strength was also greater in limbs that had undergone tendon transfers (3·9 kg) than in those that had undergone distal nerve transfers (3·2 kg). In a previous case series of 14 patients of ICSHT group 4, Reinholdt and colleagues reported a mean grip strength of 6·5 kg (range 3–14) for a single-stage grip-release reconstruction using tendon transfers and a passive reconstruction of intrinsic muscle function. Grasp strength after tendon transfer can reportedly be doubled by intrinsic reconstruction; however, to allow for rehabilitation and assessment after transfers of the nerve supplying the supinator muscle to the posterior interosseous nerve without the presence of another procedure that could confound the outcome, passive intrinsic reconstruction was not done in our study, and direct comparison is therefore not possible. Where appropriate, and desired by the patient, a passive reconstruction of the intrinsic muscles might be offered as a second-stage procedure.

Participants underwent reanimation of the anterior interosseous nerve for grasp and pinch with either proximal (nerve supplying the brachialis muscle) or distal (nerves supplying the extensor carpi radialis brevis muscle or the supinator muscle) nerve donors. The nerve to the brachialis is an appropriate donor nerve for higher-level spinal cord injury (ICSHT groups 1 and 2), but the strength achieved is not as high as that achieved by distal nerve donors, as shown in our study and in previous studies. Possible reasons for this difference include the level of spinal cord injury, the distance to the target muscle, and the potential loss of axons to other motor or sensory targets, as the transfer of the nerve supplying the brachialis is made into a fascicle of the median nerve in the arm rather than directly into the anterior interosseous nerve in the forearm. For this reason, we prefer a distal nerve transfer donor: either the nerve to the supinator muscle, in higher-level injuries (ICSHT groups 1 and 2), or the nerve supplying the extensor carpi radialis brevis, in lower-level injuries (ICSHT groups 4–7).

Where appropriate donor nerves and muscles are available for restoration of grasp and pinch, we favour a nerve transfer for one hand and a tendon transfer for the other. Participants who received both types of transfer reported that hands reconstructed with nerve transfers had a more natural appearance, were softer and more supple for social interactions, were more dextrous, and were better for grasping larger objects and for open hand tasks (such as using electronic devices). Among patients in whom the nerve supplying the supinator muscle was transferred to the posterior interosseous nerve to restore hand opening, those whose grasp and pinch had been reconstructed with nerve transfers were more satisfied with the hand opening achieved than were patients in whom grasp and pinch had been reconstructed with tendons. However, hands reconstructed with tendons felt stronger and were useful for lifting and holding heavy objects. When asked which hand they preferred,
Participants consistently reported that they liked both for different reasons and would not choose to have two hands reconstructed in the same way (video 3).

Before the development of the procedure to transfer the nerve supplying the supinator muscle to the posterior interosseous nerve, hand opening was difficult to restore. The ability to open the hand not only allows a person to use their grasp and pinch more effectively, but is essential for receiving objects, shaking hands, releasing objects, and extending the fingers and thumb to swipe, type, or use a computer mouse. In our case series, transfers of the nerve supplying the supinator muscle to the posterior interosseous nerve were consistently successful (figure 2B, C), with only one failed transfer out of the 21 for which follow-up to 24 months was available. Participants achieved median MRC grades of 4 for both extrinsic finger and thumb extension. Reanimation of abductor pollicis longus allows a wide first webspace opening and eliminates the need for thumb stabilisation procedures such as carpometacarpal joint fusion. First webspace opening in our patients who underwent transfer of the nerve supplying the supinator muscle to the posterior interosseous nerve was almost double that of the nerve supplying the supinator muscle to the posterior interosseous nerve failed uses the tenodesis effect for hand opening.

The nerve supplying the supinator muscle is the ideal donor nerve. The supinator is innervated high in the spinal cord (C5–C6 nerve roots) and is expendable because its function is replicated by the biceps muscle. Furthermore, because the nerve supplying the supinator muscle is conveniently located in the forearm—close to targets such as the posterior interosseous nerve, anterior interosseous nerve, and the nerve supplying the extensor carpi radialis brevis—the transfer distance, and therefore the time for nerve regrowth, is minimised.

Overall satisfaction with nerve transfer surgery in this case series was good. However, better functional outcomes did not always translate into greater satisfaction: some participants with the greatest use of their hands, as measured by the ARAT, GRT, or grasp strength, reported lower satisfaction with the outcome of the actual nerve transfer than did other patients who had the same transfers. This phenomenon has been reported by others and speaks to the multifactorial nature of regaining function. One issue with satisfaction is the link with expectation. Because nerve transfer surgery usually occurs early (6–12 months) after spinal cord injury, most patients who undergo these surgeries will have had little time to experience living in the community after their injury, and therefore might not fully appreciate the gains they have made following surgery. All participants in the current study set five COPM goals they wanted to achieve with the surgery. Unlike participants who underwent tendon transfer in previous studies, participants in the current study rated their performance in relation to these goals slightly more highly than they rated their satisfaction, despite their improvements being greater than what is considered clinically important.

Four of 50 nerve transfers with 24-month follow-up failed completely in this study, and all three participants in whom these failures occurred had an SNLI of C4 and an AIS category of A on admission to rehabilitation (at a mean 11 weeks after spinal cord injury). We advise caution when selecting nerve transfers as a reconstructive choice in patients who have recovered from a C4 level of injury. In the patient with failed transfers of the nerve supplying the teres minor muscle and the motor portion of the posterior axillary nerve to nerve supplying the triceps muscle, elbow extension was instead reconstructed with deltoit-to-triceps tendon transfers, and that patient subsequently has against-gravity elbow extension in both arms. The failed transfer of the nerve supplying the brachialis muscle to the anterior interosseous nerve was reconstructed successfully with a brachioradialis to flexor pollicis longus tendon transfer and an extensor carpi radialis longus to flexor digitorum profundus tendon transfer. The participant in whom the transfer of the nerve supplying the supinator muscle to the posterior interosseous nerve failed uses the tenodesis effect for hand opening.

There were several limitations to this study. Notably, spinal cord injury patterns are highly variable, as indicated by the large SDs and IQRs reported in this study. Participants also had multiple procedures to both limbs, which might have confounded data analysis, and this issue combined with the small sample size makes correlations and comparisons challenging, especially among subgroups. However, the participants were representative of patients presenting for upper extremity reconstruction at spinal cord injury units around the world, and reconstructive plans must always be tailored to injury level, availability of potential donors, functional needs, and personal preferences.

In conclusion, this study on early nerve transfer surgery in predominantly young people after traumatic spinal cord injury showed statistically significant improvements in all outcomes tested, which were similar to those reported for tendon transfers. The transfer of the nerve supplying the supinator muscle to the posterior interosseous nerve is an important advance in the restoration of hand opening. Participants appreciated the different styles of hand functionality afforded by nerve transfers for grasp and pinch on one side and tendon transfers on the other. Enhanced patient selection based on the learnings from this project could improve results further. Work to clarify the usefulness of nerve transfer surgery.
surgery in late spinal cord injury (>24 months post-injury) and at the extremes of age needs to be done. It remains to be seen whether function and strength in muscles reanimated by nerve transfers continue to improve beyond 24 months post-surgery.

Contributors

NVZ and MPG conceived the idea for the work, designed the study, interpreted the data, and wrote the manuscript. BH collected, analysed and interpreted data, prepared all tables and figures, and revised the manuscript. CC and JH designed the study, interpreted data, and revised the manuscript. All authors contributed to the literature search.

Declaration of interests

We declare no competing interests.

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