Enhancing Upper Extremity Function with Reconstructive Surgery in Persons with Tetraplegia: A Review of the Literature

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Purpose: To review the evidence for interventions in peer-reviewed published literature for reconstructive surgical procedures in the upper extremity for persons with tetraplegia following spinal cord injury (SCI). **Method**: A critical review and synthesis of articles addressing reconstructive surgical procedures was conducted. Each article was assessed for quality using the Downs and Black evaluation tool. Following this, a level of evidence using a modified Sackett scale was assigned to each intervention within these categories. **Results**: Each of the surgical procedures reviewed had numerous pre-post or case series studies that provide level 4 evidence (grade C) to support the use of reconstructive surgical procedures in improving upper extremity motor and functional use of the limb in individuals with tetraplegia following an SCI. **Conclusion**: There is evidence that reconstructive surgical procedures enhance upper extremity function for persons with tetraplegia. Although there is a need for higher quality evidence through improved study designs, there are both ethical and logistical constraints that present challenges in studying this population. **Key words:** *reconstructive surgical procedures, spinal cord injuries, tetraplegia, upper extremity*

A cervical spinal cord injury (SCI) results in tetraplegia with loss of motor and sensory function of the upper extremities. It is estimated that cervical SCI accounts for approximately 50% of all people living with SCI.[1] The loss of upper limb function, especially the use of the hands, is one of the most significant and devastating losses an individual can experience. Use of the upper extremities is critical in completing basic activities of daily living (ADLs) such as self-feeding, grooming, dressing, bathing, and toileting. Mobility needs such as transfers from surface to surface; transitional movements such as rolling, bridging, and sit to lying down; crutch walking, and wheeled mobility are also completed by using the upper extremities.[2]

The management of the tetraplegic upper limb tends to be eclectic, involving traditional rehabilitation interventions, use of orthotics (splints and adaptive devices), and

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upper extremity surgery.[3] Even though there is no overall consensus in the management of the upper limb, there is agreement that maximal restoration of hand and upper limb function is an important goal in rehabilitation.[3] Bryden et al.[4] described a hierarchy of upper extremity functional restoration for individuals with tetraplegia. The order of hierarchy begins with provision of conservative treatment methods followed by surgical restoration using residual motor functions and finally increasing or augmenting voluntary functions with functional electrical stimulation (FES) for maximal upper limb function.

Hanson and Franklin[5] reported that recovery of hand function (75.7%) was preferred to that of the bladder, bowel, or even sexual function among patients with tetraplegia. In a survey of patients with tetraplegia by Snoek et al.,[2] 75% responded that hand function was very important for independence in ADLs and quality of life. Similar results were reported by Anderson[6] in which 48.7% of persons with tetraplegia (3.3% of persons with paraplegia) reported that regaining arm and hand function would most improve their quality of life. In the same study, women and men with tetraplegia had similar priorities (53.2% to 48.3%), and the priority of regaining arm and hand function did not change whether someone was injured 0–3 years or more than 3 years previously. Anderson[6] reported that recovering even partial arm and hand function may have a significant impact on independence.

The various reconstructive surgical procedures that are performed on the upper limb have been well described and documented in the literature. Clinical practice has shown that suitable candidates for reconstructive surgery interventions often do not accept recommended treatment.[2] According to Moberg and Hentz et al., 60%–75% of the individuals with tetraplegia could benefit from reconstructive surgery.[7–12] Curtin et al.[13] reported that, despite published works and expert opinion, reconstructive surgeries are rarely done with this population. It was reported that fewer than 10% with new tetraplegia actually have these procedures.[13] The majority of the studies completed in this field are case series, which lack the rigor of high-quality randomized clinical trials.[14] The objective of the present article is to summarize the evidence for reconstructive surgery in the spinal cord–injured population.

Method

A systematic review of all relevant literature published from 1980 to 2006 using multiple databases (MEDLINE/PubMed, CINAHL®, EMBASE, PsycINFO) was conducted using SCIRE methodology as outlined separately in this issue.[15] This search involved the review of over 17,000 titles and 8,400 abstracts and final analysis of approximately 700 articles. Studies were only included for analysis if at least 50% of subjects had an SCI, there were at least three subjects, and there was a definable intervention being studied. A quality assessment was conducted for each article using Downs and Black methodology for nonrandomized studies.[16] This tool consists of 27 questions evaluating the following: reporting, external validity, and internal validity (both bias and confounding). Due to the ambiguity of the last question, a slight modification was made; thus the total score any article reviewed could receive was 28, with a higher score indicating higher methodological quality.[15]

A summary of the evidence for the various reconstructive surgical interventions was

Table 1. Grade of recommendation for summaries or reviews of orthopaedic surgical studies[19]

Grade	Description
A	Good evidence (level 1 studies with consistent findings) for or against recommending intervention.
B	Fair evidence (level 2 or 3 studies with consistent findings) for or against recommending intervention.
C	Conflicting or poor quality evidence (level 4 or 5 studies with consistent findings) for or against recommending intervention.
I	There is insufficient evidence to make a recommendation.

categorized according to various subtopic areas. The tables indicate the Downs and Black (D&B), type of study, a brief summary of intervention outcomes, and the study results.[16, 17] Levels of evidence based on a modified Sackett approach were assigned to the studies within each topic (**Table 1**). Grades of recommendation for summaries or reviews of orthopaedic surgical studies have been previously established, so a grade of recommendation was also assigned to the results (**Table 2**).[18-20]

Reconstructive Surgery

Reconstructive surgery is one option to improve the function of the hand and upper limb in persons with tetraplegia. Functionally, the benefit of reconstructive surgery is evidenced by improvements in ADLs (dressing, self-feeding, grooming) and mobility skills (propelling a wheelchair, transfers).[21] Surgery has been reported to improve quality of life for those people who had little or no upper limb function.[22]

Table 2. Levels of evidence[17]

Level	Research design	Description
1	Randomized controlled trial (RCT)	RCT, PEDro ≥6. Included within-subjects comparison with randomized conditions and crossover designs.
2	RCTs	RCTs, PEDro <6.
	Prospective controlled	Prospective controlled trials, nonrandomized.
	Cohort	Prospective longitudinal study using at least 2 similar groups with one exposed to a particular condition.
3	Case control	A retrospective study comparing conditions, including historical controls.
4	Pre-post	A prospective trial with a baseline measure, intervention, and posttesting using a single group of subjects.
	Posttest	A prospective posttest with 2 or more (no baseline measure) using a single group of subjects.
	Case series	A retrospective study usually collecting variables from a chart review.
5	Observational	Study using cross-sectional analysis to interpret relations.
	Clinical consensus	Expert opinion without explicit critical appraisal or based on physiology, biomechanics, or “first principles.”
	Case report	Pre-post or case study involving 1 subject.

Reconstructive surgery and tendon transfers are generally performed following an identifiable pattern based on the level of injury, and results depend on the patient's residual motor and sensory function as identified in each group.[23] In 1978, the International Classification for Surgery of the Hand in Tetraplegia was developed at the International Conference held in Edinburgh and modified in 1984.[23]

The classification takes into account the residual motor strength below the elbow, considering that only the muscles graded 4 or 5 according to the Medical Research Council Scale (MRCS) are adequate for muscle transfer, as well as the sensibility in thumb and index finger. The sensibility is evaluated by the two-point discrimination test in the thumb and the index finger. If the score is lower than 10 mm, the classification belongs to the group Cutaneous (Cu-); if it is higher than 10 mm and the patient needs visual help, it is classified in the group Ocular (O-).[23]

Candidates for reconstructive surgery are at least 1 year postinjury, have completed a comprehensive rehabilitation program, are neurologically stable, are psychologically adjusted to their injury, and are carefully followed by a rehabilitation team that includes an orthopedic surgeon, rehabilitation physiatrist, and therapist over a significant period of time.[7,9–11] General consensus and expert opinion in the medical community agree that upper extremity surgery is beneficial; however, hand and upper limb reconstructive surgery is not common practice in many spinal units.[24] Upper limb reconstructions designed to regain pinch and grasp and elbow extension often require multiple procedures and are individualized to each person. The reconstructions are also dependent on the presence of muscles/tendons strong enough for transfer.

Reconstructive pinch

The most commonly performed surgeries for reconstructive pinch are the following:

- *Key-pinch grip*: Brachioradialis (BR) to extensor carpi radialis longus (ECRL), flexor pollicis longus (FPL) tenodesis. The IP joint of the thumb may need to be stabilized to prevent excessive IP flexion.
- *Key-pinch grip with or without hook grip*: BR to flexor pollicis longus (FPL) with or without flexor digitorum profundus (FDP) tenodesis or BR to ECRL.
- *Key-pinch grip and hook grip*: BR or pronator teres (PT) to FPL and BR or ECRL to FDP.

Additional procedures to increase thumb pinch and thumb opposition may also be completed. Studies using these procedures are summarized in **Table 3**.

Discussion

In all three studies, study subjects reported an improvement in their overall grip strength and improvement in their ability to perform ADLs. House et al.[25] also reported that those who underwent surgery had a more reliable and reproducible key pinch. McCarthy et al.[26] found that subjects who underwent an intrinsic procedure had stronger grip strength than patients who did not participate in the procedure. In the study by Waters et al.,[27] subjects found an improvement in lateral pinch and ADL function in the operated hand. Overall, subjects in each study reported that they felt that the surgery was a success.

Conclusion

There is level 4 evidence (grade C) from three pre-post and case series studies that reconstructive surgery to improve pinch resulted in improved pinch strength and the

Table 3. Reconstructive surgery: pinch studies

Author, year **Country** **D&B Score** **Design**	**Method**	**Results**
Waters et al., 1985[27] USA D&B = 12 Case series	**Population:** N = 15; Age: range 20–47 yrs; Injury to operation: range 8–18 yrs; Operation to follow-up: range 8–48 months; Gender: M = 13, F = 2. **Treatment:** Surgery. **Outcome measures:** Pinch strength; ADL reports.	1. Lateral pinch improved postsurgery. 2. ADLs improved postsurgery. 3. 87% felt surgery was a success—significant function improved in the hand.
House et al., 1992[25] USA D&B = 11 Case series	**Population:** N = 18; Gender: M = 14, F = 4; Level of injury: C5-C6; Age: 16–29 yrs; Time to surgery: 16 months to 12–13 yrs. **Treatment:** Carpal-metacarpal fusion was performed; along with extensor pollicis longus tenodesis and motor transfer to flexor pollicis longus. **Outcome measures:** Function of the hand, subjective pain scale, and level of satisfaction with surgery and rehabilitation.	Follow-up 1–10 yrs (average 3.5 yrs): 1. All patients reported a significant increase in independent hand function in relation to ADLs; no patient-reported hand function was worse after surgery. 2. Technique provided a reliable and reproducible key pinch. 3. All patients had significant improvement in functional ADLs and highly satisfied with results of surgery.
McCarthy et al., 1997[26] USA D&B = 10 Pre-post study	**Population:** N = 135; Gender: M = 103, F = 30; Age: 8–58 yrs; Tetraplegia; Follow-up: 3–24 months. **Treatment:** Extrinsic hand reconstruction with intrinsic balancing procedures vs. extrinsic reconstructions without intrinsic balancing procedures. **Outcome measures:** Pre- and postoperative assessments of grip strength (on the second position of the Jamar dynamometer) and a patient questionnaire evaluating 31 ADLs.	ADL and grip strength improved postsurgery. 1. Patients who underwent an intrinsic procedure had a statistically stronger grip (72 N) than patients who did not undergo an intrinsic procedure (p = .026). 2. Oculocutaneous (OCU) group; 5 patients (n = 35) with an intrinsic procedure had a statistically stronger grip than patients without an intrinsic procedure (p = .028). 3. There was significant difference between the hands treated by flexor digitorum superficialis (FDS) lasso and those treated by intrinsic tenodesis when patients were stratified by OCU level.

Note: D&B = Downs and Black quality assessment scale score.[16] ADL = activities of daily living; F = female; M = male; yr = year.

study subject's ability to complete various ADL and functional tasks.

Reconstructive pinch and grip

The most commonly performed surgeries to obtain key-pinch and hook grip include the following (**Table 4**): extensor carpi radialis longus (ECRL) to flexor digitorum profundus (FDP). This is a synergistic transfer in which dorsiflexion of the wrist potentiates the effects of the transfer. The amplitude of excursion provides strong flexion of the fingers into the palm. Brachioradialis (BR) is also transferred to flexor pollicis longus (FPL). The aim of these transfers is to provide mass finger flexion for grasp and independent thumb flexion for key pinch against the side of the middle phalanx of the index finger. Adjustment of tension in these transfers is also completed.[28] If the person does not have adequate wrist extension, BR to extensor carpi radialis brevis (ECRB) is performed prior to any surgery for pinch reconstruction.

Discussion

Forner-Cordero et al.[24] reported that subjects who underwent the surgical reconstruction procedure experienced an increase in their key-pinch and grasp strength and also reported an increase in their ADLs. Colyer and Kappleman[29] found that subjects reported an improvement in hand function and key-pinch. Although no statistically significant findings were reported in the other studies, it was noted that subjects did indicate an improvement in their abilities to perform ADLs[30–32] and overall they were pleased they had decided to proceed with surgery.[32–34] One study by Rieser and Waters[35] found that over time subjects reported a decrease in hand strength. The authors indicated various reasons for these findings.

Conclusion

There is level 4 evidence (grade C) from seven of eight pre-post and case series studies reviewed that various reconstructive surgical procedures used to improve key-pinch and hook grip resulted in improved pinch and grip strength, which led to an improvement in the patient's ability to complete ADLs. One study reported that over time subjects reported a decrease in hand strength.

Elbow extension reconstructions

Posterior deltoid to triceps

The most commonly performed surgery for elbow extension uses the posterior third of the deltoid (PD) to motor the triceps. This converts the transferred portion of the deltoid into a two joint muscle without functional loss at the shoulder.[7] Study summaries using this procedure are shown in **Table 5**.

Discussion

Rabischong et al.[21] assessed the length-tension relationship of posterior deltoid to triceps transfer of the study subjects compared to a sample of able-bodied right-handed females using a force transducer to assess torque output at various positions of elbow flexion with the shoulder abducted at 90º. The study showed that the patients who had the transfer had lower torque output than the comparison group. Also, the length-tension relationship of the posterior deltoid to triceps remained consistent in the comparison group but variable in the study group, which presented a challenge for surgeons in determining optimal tension at the time of surgery. Remy-Neris et al. found that improving elbow extension in the study subjects played a key role in improving the speed of elbow flexion and was important in the

Table 4. Reconstructive surgery: pinch and grip studies

Author, year **Country** **D&B Score** **Design**	**Method**	**Results**
Forner-Cordero et al., 2003[24] Spain D&B = 5 Retrospective follow-up	**Population:** *N* = 15; Age at first operation: 20–62 yrs; Level of injury: C4-C7; Time from injury to operation: 15–239 months. **Treatment:** Surgical reconstruction. **Outcome measures:** Increased hand movement and strength; improvement in ADL; patient's satisfaction, fulfillment of patient's expectations, surgical complications.	1. Strength: key-pinch strength average of 17.2 kPa (5–50 kPa); grasp strength average 18.8 kPa (3–45 kPa). 2. No relation found between the ADL test and the key-pinch strength (p = .7976) or grasp strength (p = .6948). 3. Modification of ADL questionnaire; excellent (3) 21.4%; good (7) 50.0%; fair (2) 14.3%; poor (2) 14.3%. Scores ranged from 54–122 points.
Meiners et al., 2002[32] Germany D&B = 10 Case series	**Population:** *N* = 24; Gender: F = 3, M = 21; Age: 21–57 yrs; Time since injury: 9–59 months. **Methodology:** Surgery. **Outcome measures:** ADL questionnaire, satisfaction survey, key grip and lateral force grip.	No statistical findings reported. 1. Operative interventions on the tetraplegic hand brings gains in cylindrical and lateral grip and improvement in ADL. 2. Subjective acceptance is high.
Lo et al., 1998[34] Canada D&B = 7 Case series	**Population:** *N* = 9; at least 1 yr postinjury **Intervention:** Surgery. **Outcome measures:** Not specified.	No statistical results reported. 1. All reported they would have surgery again. 2. Key-pinch strength in nonoperative limbs was 1.0 ± 1.3 kg; in surgically treated arms it was 1.2 ± 1.1 kg. 3. Minnesota rate of manipulation: nonoperative limbs were 1 min 29 s ± 15 s; postoperative limbs were 2 min 56 s ± 1 min 56 s.
Failla et al., 1990[30] USA D&B = 6 Case reports	**Population:** *N* = 8; Age: 9–58 yrs; Tetraplegia. **Treatment:** Surgery. **Outcome measures:** Key-pinch, grip strength, function in ADL.	1. 5 subjects completed questionnaire on ADL and were tested by measurement of key-pinch and grip strength and hand function. 2. Conclusion: transfer of brachioradialis tendon provides key-pinch and grip of sufficient quality to improve the ADLs in patients with loss of flexion of the thumb and fingers.

Gansel et al., 1990[31] USA D&B = 4 Case series	**Population:** N = 19; Age at time of surgery: 20–47 yrs. **Intervention:** Surgery. **Outcome measures:** Not specified.	No statistical analysis reported. 1. Passive range of motion of the elbow and wrist remained unchanged postsurgery. Functional active flexion of the fingers was gained in 10 of 11 subjects. 2. Improved performance of ADLs was reported.
Rieser & Waters, 1986[35] USA D&B = 8 Case series	**Population:** N = 23; Age: mean = 23.6 yrs; Age at time of surgery: mean = 29.8 yrs; Time from injury to operation: 6.2 yrs; Follow-up time of this study: 7.4 yrs. **Intervention:** Surgery. **Outcome measures:** Not specified.	No statistical results reported. 1. 80% of the subjects reported that the surgery enhanced their functional independence. 2. Self-assessment questionnaire results indicated pinch power progressively decreased since surgery in all patients.
Kelly et al., 1985[33] USA D&B = 9 Case series	**Population:** N = 24; Age: 19–60 yrs; Age at injury: 15–46 yrs; Injury to operation: 1–17 yrs; Follow-up postop: 1–17 yrs; Gender: M = 17, F = 7; Level of injury: 3 in group 3, 11 in group 4, 7 in group 5, 4 in group 6. **Intervention:** Surgery. **Outcome measures:** Not specified.	1. Subjects reported that they would have the operation again (95% of the extremities) and had improved function (91%). 2. Grasp measured in 20 extremities; 2.81 ± 2.89 kg (mean ± *SD*) (range, trace to 10 kg). 3. Palmar pinch: 9 of 20 extremities (45%) achieved palmar pinch (1.04 ± 1.02 kg; mean ± *SD*) (range, 0.20–3.0 kg). 4. Palmar pinch achieved in 17% of the extremities in group 3, 71% in group 4, and 33% in group 5.
Colyer & Kappelman, 1981[29] USA D&B = 7 Case series	**Population:** N = 8; Age: 16–36 yrs; Time postinjury: 4 months to 18 yrs. **Intervention:** Surgery. **Outcome measures:** Not specified.	No statistical results reported. 1. Subjects (n = 6) indicated they were pleased with the surgery. 2. Hand function tests indicated an improvement (16%–49% improvement). 3. 5 of 6 subjects showed key grip strength remained constant.

Note: D&B = Downs and Black quality assessment scale score.[16] ADL = activities of daily living; F = female; M = male; yr = year.

Table 5. Reconstructive surgery: elbow extension studies (posterior deltoid to triceps)

Author, year Country D&B Score Design	Method	Results
Dunkerley et al., 2000[37] UK D&B = 13 Case control	**Population: Surgical cases,** *N* = 5; Age: 23–37 yrs; Time since injury: 5–16 yrs; Age at time of injury: 18–27 yrs; Time since surgery: 1.5–3 yrs. **Nonsurgical controls,** *N* = 10; Age: 29–38 yrs; Age at injury: 21–23 yrs; Time since injury: 7.5–15 yrs. **Treatment:** Surgery—followed by questionnaire. **Outcome measures:** FIM™ used to quantify the performance of ADLs, the 10-m push, and the figure of 8 push.	1. 4 of the nonsurgical controls were not included in analysis, therefore *n* = 6. 2. **FIM scores:** Both groups (surgical and nonsurgical group) scored identically. 3. **Mobility:** No significant differences were noted ($p = .256$ and $p = .432$) between the two groups. 4. **Questionnaire:** Answered only by the treatment group—clients gave positive response to the questions.
Remy-Neris et al.,[36] 2003 France D&B = 13 Pre-post	**Population:** *N* = 17; Gender: M = 11, F = 5; Age: mean 27 yrs; ASIA score: 16–20. **Treatment:** Control group members sat on a chair, while the tetraplegics sat in a wheelchair. All were asked to perform 2 movements: a straight arm lateral and maximal raising and return. **Outcome measures:** Straight arm raising and hand-to-nape-of-neck movement.	1. Straight arm raising: Statistically significant decrease in maximal shoulder abduction (before surgery, mean = 57, SEM = 12; after surgery, mean = 14, SEM = 6). 2. Shoulder flexion increased after deltoid-to-triceps transfer by 42% (mean = 113, SEM = 11) and remained significantly lower (mean = 121, SEM = 12) than control group ($p < .0001$). 3. Hand-to-nape-of-neck movement: No significant improvements were noted after surgery. 4. Conclusion: Peaks of shoulder and elbow flexion speed are almost normal, indicating the importance of restoring elbow extension torque for improving the whole kinematic picture of the upper limb.

Rabischong et al., 1993[21] France D&B = 16 Pre-post	**Population: Experimental group,** N = 12; Age: mean 33.6 yrs; Level of lesion: C6; Time since injury: 28–173 months; Time prior to surgery: 34.5 yrs; Time since surgery: 46.1 months. Control group: N = 9 able-bodied right-handed females; Mean age, 29.5 ± 3.6 yrs. **Treatment:** The arm and forearm were locked in position and a force transducer was used to assess the torque output isometrically. The muscle was tested at 6 different lengths with the shoulder abducted at 90°. **Outcome measures:** Maximal torque and absolute values.	1. The length-tension relationship of the posterior deltoid to triceps transfer was tested at 130°, 110°, 90°, 70°, 45°, and 0° of elbow flexion with the shoulder abducted at 90°. 2. When compared, the absolute values (dimension of torque) were significantly different between groups (.00001 < p < .002). 3. The expression of this relation (% of maximum values) revealed significant statistical differences (p < .002) at 90° and 70° of elbow flexion; peak torque 130° in experimental group; 110° in control group; plateau between 110° and 70°. 4. Length-tension relationship remained similar in the comparison group but was variable in the study group. Initial length-tension relationship at the time of surgery is important in overall outcome.
Lacey et al., 1986[38] USA D&B = 7 Case series	**Population:** N = 10; Level of injury: C6 or C7; Time since injury: average 24 months; Time to operation: approx 32 months. **Treatment:** Surgery. **Outcome measures:** Not specified.	No statistical results reported. 1. No statistically significant differences between pre- and postoperative stages. 2. Activities that were noted as improved were the overhead use of the arms, use of arms while lying supine, and eating.
Raczka et al., 1984[39] USA D&B = 4 Case series	**Population:** N = 22; Time since injury: average 10–242 months; Time to surgery: 64.1 months. **Treatment:** Surgery. **Outcome measures:** ADLs, use of wheelchair.	No statistical analysis reported. 1. 15/18 reported function improvement after surgery; 13 felt they gained an increase in independence. 2. Functional improvements and grooming was noted. 3. Improvements were noted in subject's ability to relieve ischial pressure from their wheel chair, writing improved, and driving is a small percentage was positively affected.

Note: D&B = Downs and Black quality assessment scale score.[16] ADL = activities of daily living; ASIA = American Spinal Injury Association; F = female; M = male; yr = year.

movement and speed of shoulder flexion in both upward and downward phases.[21,36]

Dunkerley et al.[37] did not find any significant differences between the subjects who underwent surgery and those who did not when comparing results of the FIM™* and mobility tests (10-m push; the figure of 8 push test). Similar findings were noted by Lacey et al. and Raczka et al. in each of their studies.[38,39] Although neither study included any statistical analysis, they did include subjective reports from subjects that indicated that improving elbow extension led to improved overhead reaching ability required to complete grooming tasks, ischial pressure relief, and pushing their wheelchair.[38,39]

Conclusion

There is level 3 (grade B) evidence from one case-control study and level 4 (grade C) evidence from four pre-post or case series studies indicating that improving patients' ability to extend their elbow also improves shoulder functions, which leads to an improvement in ADL function and use of their wheelchair.

Biceps to triceps transfer

Another option available to patients is the biceps to triceps transfer. This procedure can also be used to create elbow extension in patients who have active supinator and brachialis muscles to provide for the lost functions of the transferred biceps.[40] The studies summarizing the use of this procedure are shown in **Table 6**.

Discussion

Kuz et al.[40] found that overall subjects were satisfied with the surgery. It was also reported by the study subjects that improved elbow extension resulted in improved ability for distal control of the hand required for precise placement when performing grasping and pinching activities. The study also reported that study subjects were able to discontinue the use of some adaptive devices postsurgery.[40] Revol et al.[41] also found that active extension (range of motion [ROM]) of the elbow and supination of the forearm was maintained following surgery, however there was a decrease in elbow flexion torque (47%); this did not appear to affect the ability to perform various ADLs.

Conclusion

There is level 4 evidence (grade C) from two case series studies that demonstrate improving a patient's ability to extend their elbow through a biceps to triceps transfer resulted in the patient having improved distal hand control needed to complete functional activities. The resultant decrease in bicep strength did not appear to affect function of the upper limb.

Comparison of two surgical approaches

Mulcahey et al.[42] directly compared results of two surgical groups (posterior deltoid to triceps, biceps to triceps) to determine if there were any differences in surgical outcomes. The study did not show any significant differences between the two groups for flexion torque, ADL scores, and performance and satisfaction with self-selected goals. However, they did note clinically, although not statistically significant, the biceps to triceps group appeared to have stronger antigravity

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*FIM™ is a trademark of Uniform Data System for Medical Rehabilitation, a division of UB Foundation Activities, Inc.

Table 6. Reconstructive surgery: elbow extension studies (biceps to triceps transfer)

Author, year **Country** **D&B Score** **Design**	**Method**	**Results**
Kuz et al., 1999[40] USA D&B = 7 Level 4 case series	**Population:** $N = 3$; Tetraplegic. **Treatment:** Surgery. **Outcome measures:** Not specified.	No statistical results reported. 1. Subjects indicated they were satisfied with the surgery. 2. Activities that required precision hand placement had improved. 3. Elimination of the need for some adaptive aids was possible postsurgery.
Revol et al., 1999[41] France D&B = 5 Level 4 case series	**Population:** $N = 8$; Tetraplegic; Gender: F = 1, M = 7; Age range: 22–47 yr; Side: R = 6, L = 7. **Treatment:** Surgery. **Outcome measures:** Not specified.	1. Active extension of elbow was obtained. 2. Postoperative ROM of the elbow was 6° extension and 137° flexion. 3. Mean flexion torque of the elbow was 17.1 Nm (*SD* 12.1) pretransfer; this was decreased to 9.0 Nm (*SD* 5.3) posttransfer, which did not appear to have a negative effect on subjects.

Note: D&B = Downs and Black quality assessment scale score.[16] F = female; L = left; M = male; R = right; ROM = range of motion; yr = year.

elbow extension. Both groups also had a 47% decrease in flexion torque at 2 years postsurgery, which is similar to the findings reported by Revol et al.[41] Mulcahey et al.[42] study summary is available in **Table 7.**

Conclusion

There is level 2 evidence (grade B) from one prospective controlled study that having either the deltoid to triceps or biceps to triceps transfer results in comparable outcomes for flexion torque, ADL performance, and client satisfaction with self-selected goals.

Multiple reconstructions

Table 8 summarizes the studies reporting results from multiple and mixed procedures in the reconstruction of a single arm.

Discussion

The studies that were reviewed reported a wide variety of surgical approaches and many different outcome measures, making comparisons between the various studies difficult.

Overall, very few statistical results were reported, but all studies reported that the subjects seemed generally satisfied with their surgical results and their increased ability to perform various ADLs. Most subjects felt they had greater hand or thumb function. In addition, Rothwell et al.,[43] Ejeskar and Dahllof,[44] and Lamb and Chan[28] reported that there was improvement in elbow extension postsurgery. It was also noted in one study that hook grip strength and pinch grip strength increased postsurgery; when the group was looked at 10 years later, this finding was maintained.[43]

Conclusion

There is level 2 evidence (grade B) from one prospective controlled study and level 4 evidence (grade C) from seven pre-post or case series studies that reconstructive surgery that improves pinch, grip, and elbow extension functions results in an improvement in both ADL performance and quality of life in tetraplegia.

Summary

The majority of the studies are of lower methodological quality (case series, level 4, grade C). The various studies consistently reported improvement in grip and key-pinch strength, elbow extension, and various aspects of ADLs. Study subjects also consistently reported satisfaction with the improvements and functional gains obtained and would elect to have surgery again.

Standardized outcome measures have not been consistently used and/or identified in these studies. Many of the tools for measuring grip and pinch strength need to be specially designed and are not consistently available in clinical settings.[43] Many of the questionnaires are developed or modified for a particular study; therefore, there is little to no evidence to suggest that the questionnaires are statistically valid and reliable. The majority of the studies used subjective reports from participants that assessed their satisfaction with reconstructive surgery. Outcomes of the various surgeries performed are commonly measured by the following: measurement of key-pinch and grip strength, ROM, ability to grasp and release, ability to perform standardized tasks, ability to perform ADLs, and self-reports of satisfaction.[3]

Due to the variability of patient presentation, the individualized needs of each patient, numerous surgical approaches, and different assessment tools for evaluation used within the studies comparing results between stud-

Table 7. Reconstructive surgery: elbow extension biceps to triceps and posterior deltoid to triceps

Author, year **Country** **D&B Score** **Design**	**Method**	**Results**
Mulcahey et al., 2003[42] USA D&B = 18 Prospective controlled	**Population:** $N = 9$; Gender: M = 7, F = 2; Level of injury: C5-6; ICSHT: 0–4; Tendon transfer for elbow extension: biceps $n = 8$, deltoids $n = 8$. **Treatment:** Surgery. **Outcome measures:** Flexion torque, muscle strength, Modified University of Minnesota Tendon Transfer Functional Improvement Questionnaire, Canadian Occupational Performance Measure.	1. Following surgery, both biceps and deltoid groups had increase in elbow extension muscle strength ($p < .001$). 2. Elbow extension muscle strength showed no significant improvement postsurgery. 3. Antigravity muscle strength improved clinically in 7 of 8 biceps-to-triceps procedures done compared to improvement in only 1 of 8 deltoid transfers performed. 4. Flexion torque: No significant differences in elbow flexion torque between groups (47% decrease in torque compared to baseline at the end of 2 yrs). 5. ADL: Subjects did report an improvement in ADLs postsurgery in 48/63 elbow extension activities; no change in 15/63 elbow extension activities. 6. COPM: Postsurgery, both groups indicated their performance and satisfaction with self-selected goals had improved.

Note: D&B = Downs and Black quality assessment scale score.[16] ADL = activities of daily living; COPM = Canadian Occupational Performance Measure; F = female; ICSHT = International Classification for Surgery of the Hand and Tetraplegia; M = male.

Table 8. Reconstructive surgery: multiple reconstructions

Author, year **Country** **D&B Score** **Design**	**Method**	**Results**
Rothwell et al., 2003[43] New Zealand D&B = 20 Pre-post	**Population:** N = 24; Age: mean 42.9 yrs; Mean time since injury: 20.5 yrs; Mean time since surgery: 15.1 yrs; 22/24 right-handed; Tetraplegia. **Treatment:** Surgery. **Outcome Measures:** Lamb and Chan questionnaire with additional 10 Burwood questions, Swanson sphygmomanometer (hook grip), Preston Pinch Meter (key-pinch), Quadriplegic Index of Function (QIF), Digital Analyzer (DA) (key and grip pinch).	1. Elbow extension: Hook grip; 17 right hands improved slightly and 15 left hands had significant increase ($p \leq .001$) 2. Key pinch: Decreased significantly over the 10-yr period ($p \leq .001$); average pinch strength decreased significantly ($p \leq .001$). Average pinch strength increased significantly for both thumbs ($p = .01$). 3. Active transfer vs. tenodeses: Hook grip: active transfers 2x strength of tenodeses in 1991 ($p = .05$) and 2001 ($p = .03$). Pinch grip: Decreased over the 10-yr period ($p < .05$). 4. Longitudinal comparison: Hook grip strength increased ($p \leq .001$) and pinch grip increased ($p = .03$). Hook strength obtained from a tenodesis in 7 hands did not weaken over time ($p = .05$) but pinch strength in 7 thumbs significantly increased ($p \leq .001$). 5. Questionnaire results: perceived improvement of functional activities significantly lower in 2001 ($p \leq .001$). QIF scores of current functional independence was statistically significantly better ($p = .004$).

Welraeds et al., 2003[45] Belgium D&B = 12 Case series	**Population:** N = 25; Age at time of injury: mean 30 yrs; Age at time of operation: mean 37 yrs; Time between injury and surgery: 7–356 months; Injury level: C5-C8. **Treatment:** Upper limb surgery. **Outcome measures**: Functional testing.	No statistical analysis provided. 1. Gestural ability improved in more than 80% of the patients and functional gain was important in more than half. 2. 43 procedures were completed; these included: • Atypical procedures: 2 completed; self-reports by subjects as having a good outcome. • Moberg procedures: 18 completed; self-reports by subjects as 17 good and 1 poor outcome. • Deltoid/triceps: 12 complete; self-reports by subjects as 7 good, 3 fair, and 2 poor out-comes. • Additional procedures: 11 completed; self-reports by subjects as 7 good, 3 fair, and 1 poor outcomes.
Wuolle et al., 2003[3] USA D&B = 7 Questionnaire	**Population:** N = 73; Gender: M = 53, F = 14; Tetraplegia; Age at time of injury: 16–75 yrs; Time for injury to surgery: 1–33 yrs. **Treatment:** No treatment, questionnaire. **Outcome measures:** Not specified.	No statistical results reported. 1. 70% indicated they were satisfied with surgery. 2. 77% of responses were positive for effect on life; 67% indicated they were more indepen-dent. 3. Of those who worked (n = 21), 69% answered positively to the questions about their occupation. 4. 86% felt surgery helped them function. 5. 83% of responses indicated function change was better or much better as a result of surgery.
Freehafer, 1998[58] USA D&B = 10 Case series	**Population:** N = 285; Neurological levels: C5-C8. **Treatment:** Surgical reconstruction. **Outcome measures:** Not specified.	1. Opponens transfers were done 180 times; transfers for finger flexion 161 times; posterior deltoid transfers 59 times; transfers for wrist extension 17 times. 2. 13 out of 285 stated that they were no better, and no patient said they were worse.

(c0ntinued)

Table 8. Continued

Author, year **Country** **D&B Score** **Design**	**Method**	**Results**
Mohammed et al., 1992[59] New Zealand D&B = 12 Case series	**Population:** *N* = 57; Age: average age at first operation 27 yrs (5–55 yrs); Gender: M = 51, F = 6; Tetraplegia. **Treatment:** Surgery. **Outcome measures**: Subject assessment of ADL by questionnaire; objective assessment of key-pinch (Preston Pinch Meter); hook-grip strength (modified sphygmomanometer); elbow extension: MRC grading system.	1. Subjective assessment: Obtained for 86% of the patients; 70% reported good or excellent results, 22% fair, 8% poor. 2. Simultaneous surgery for key-grip and hook grip strength, 96% good or excellent results. 3. Objective results: >70% of patients, average follow-up of 32 months; key-pinch 52/68 cases (76%); average strength was 2.1 kg. Hook grip measured in 42/58 cases (72%), thumb included average strength was 42 mmHg; thumb excluded 29 mmHg. 4. Elbow extension measured in 71% of patients, obtained grade 3 or 4 strength.
Ejeskar & Dahllof, 1988[44] Sweden D&B = 11 Case series	**Population:** *N* = 43; Age: born between 1918–1962; Gender: F = 7, M = 36; Tetraplegia. **Treatment**: Surgery. **Outcome measures:** Questionnaire of 55 ADL tasks; opinion of the effect of surgery to perform these ADL tasks; elbow extension (evaluation of extension deficit or holding a sand bag in hand); key grip pinch (Preston Pinch Guage); finger flexion (Martin Vigorimeter).	1. Elbow extension: 30 elbows in 23 patients (23/30 with free tendon graft; 7/30 Castro-Sierra and Lopez-Pita method; 5/23 with free tendon graft); 1/23 full ext.; 8/23 lack ext. against gravity of max. 60; 10/23 lack even more ext.; 6/7 ext. deficit greater than 60. 2. Key grip: 50 hands/40 patients; strength 0–3.5 kg (average 0.7 kg); 15 patients had minimum of 1.0 kg. 3. Finger flexion: 14 hand/13 patients (ECRL to profundi II-V); grip 0–0.27 kP (average 0.13 kP); 5/14 minimum strength 1.0 kg.

		4. ADL tasks: 4 patients reported no improvement; 4/43 could not state how much they had improved; 35/43 average improved capacity to perform 23/55 ADL tasks; 3/43 patients a functional deterioration.
Freehafer et al., 1984[22] USA D&B = 12 Case series	**Population:** *N* = 68; Age at time of surgery: 15–61 yrs; Time since injury to surgery: 1–17 yrs; Tetraplegics. **Treatment:** Surgical reconstruction. **Outcome measures:** Comparison of the postsurgical with the presurgical condition.	1. 142 transfers were performed on 68 subjects. 2. No upper limbs were made worse. 3. 4 remained unimproved, all others that had tendon transfers improved.
Lamb & Chan, 1983[28] UK D&B = 14 Case series	**Population:** *N* = 41; Age: 21–59 yrs (average 29 yrs); Gender: M = 38, F = 3; Complete injuries; Average follow-up after operation: 6 months to 25 years; Tetraplegia. **Treatment:** Surgery. **Outcome measures:** Elbow strength; hand function (assessment checklist developed); ADL (developed checklist).	1. Elbow function: 10/16 elbows (10 patients): full extension; 2/16 elbows 20º flexion contracture; 4/16 15º of extension lag. All considered the procedure beneficial. 2. Hand function: No patient had any impairment of hand function after operation. 3. ADL: 29 patients assessed; some improvement was noted.
Hentz et al., 1983[8] USA D&B = 4 Case reports	**Population:** *N* = 30; Level of injury: OCu 1,2,3. **Treatment:** Reconstruction of key grip and active elbow extension. **Outcome measures:** Interview and/or questionnaire (self-care, communication, mobility); objective measurements pre- + postop strength, ROM wrist + elbow extension, strength of key-pinch, range of passive wrist flexion + functional testing.	No statistically significant findings reported. Subjective client reports. 1. Poor results: 5 subjects were dissatisfied with hand function postsurgery. 2. Fair results: 7 subjects were moderately satisfied with surgical results. 3. Good results: 11 subjects were pleased with surgical results.

Note: D&B = Downs and Black quality assessment scale score.[16] ADL = activities of daily living; ECRL = extensor carpi radialis longus; F = female; M = male; ROM = range of motion; yr = year.

ies presents many challenges.[45] It has been suggested in the literature that comparison of postsurgical conditions is regarded by many as the best way to evaluate results.[46] It can be argued that due to the lack of high-quality research studies (especially randomized controlled trials) the risks and benefits of various surgeries may not be accurately reported (adverse complications, patient compliance with lengthy immobilization and rehabilitation periods).[42]

In the studies by Curtin et al.,[13,47] it was reported that reconstructive surgery is underused in this population. Possible factors for this underutilization included the unavailability of surgeons to complete these surgeries due to already over-extended practices, lack of appropriate referral networks between physiatrists and surgeons, and lack of overall knowledge of these procedures within the medical community.[13,47] It was interesting to note that Curtin et al.[13] did not find evidence that cost or payment was an issue. However reconstructive surgeries are expensive when the overall costs are considered. Required resources, both physical and personnel, are usually only found in specialized rehabilitation centers. The financial costs incurred by the client include cost of attendant care during the postoperative immobilization and rehabilitation phase, travel costs to and from therapy, and the possible financial loss for time away from work. Many clients are also concerned that surgery might have a negative impact, especially the potential risk for a decrease in hand function. Many clients delay pursuing surgical options that might potentially interfere with hand function should a cure for SCI be found.[6]

The International Campaign for Cures of Spinal Cord Injury Paralysis (ICCP), an international panel of experts, reviewed the methodology for clinical trials for SCI and provided recommendations on the conduct of future trials.[1,48–50] The ICCP panel recommended that there is a need to improve study designs to include multicenter trials and trials with a control group or parallel nonoperated group. Also examiners should be blinded; there should be at least single-blinded assessment of study outcome(s). It was noted by the panel that there are both logistical and ethical constraints in performing randomized controlled trials. The ICCP panel also identified that one of the top priorities is to validate a functional outcome tool to assess arm and hand capacity after a cervical spinal injury; there is little consensus in the literature on the assessment instruments and tools to be used in this population as the reliability, validity, and responsiveness have not been adequately proven.[51] Majority of the hand and upper limb tests developed have been with the domains of stroke or hand surgery and do not describe the impairment and course of hand function recovery after SCI, particularly for acute tetraplegic patients.[1]

The ICCP panel recommended that the assessment of the hand function has to include several components: (a) proximal arm and trunk stabilization (reaching out) as well as placement of the arm and hand; (b) sensory testing of at least two sensory qualities (touch sensation, vibration, temperature, two-point discrimination, proprioception); (c) manual muscle testing of intrinsic (small hand) and extrinsic (forearm) muscles involved in hand control; and (d) a description of different grasp forms and the effect of tenodesis on hand function, specifically for opening and closing of finger and the fist.[1]

Several assessment tools were identified by the ICCP panel for consideration: Quadriplegia Index of Function, Sollerman Test, Manual Muscle Test, Action Research Arm Test, Jebsen (Taylor) Test. Several other upper limb outcome assessment tools recently introduced (Motor Capacities Test, Tetraplegia Hand Measure) are undergoing further testing and validation.[1] The ICCP panel identified that there is an initiative underway in many countries to develop an integrated hand function test as a valid assessment tool for SCI clinical trials.[1]

The ICCP panel also recommended that studies include a comprehensive functional outcome tool such as the FIM™ or Spinal Cord Independence Measure (SCIM) and a Quality of Life Survey (QoL). Inclusion of a QoL assessment is often recommended as an outcome measure to be included in a clinical trial, although often as a secondary outcome.[1] Two examples given for a QoL assessment included the SF-36 (Medical Outcomes Study 36-item Short-Form Health Survey) and SWLS (Satisfaction with Life Surveys).[1]

At the Eighth International Upper Limb Surgery and Tetraplegia Meeting (2004), the use of the Canadian Occupational Performance Measure (COPM)[52–56] was recommended as one of the measurement tools to be used in research.[4] Several articles also have been published that propose the use of the International Classification of Functioning, Disability and Health (ICF) conceptual framework for various measures of handicap, social integration, employment, life satisfaction, quality of life, and interaction with the environment as a way to interpret hand function outcomes following surgery.[4,57]

There is a need to establish an assessment tool that can accurately assess hand and upper limb function of persons with tetraplegia. Recording and reporting of these results need to be consistent by all service providers. Multicenter trials with improved/higher quality study design (e.g., randomized controlled trials to generate level 1 or 2 evidence) need to be completed to accurately report the true risks and benefits of undergoing reconstructive surgery of the upper limb. Due to relatively low sample sizes in these studies compared to pharmaceutical trials, better tracking of clients eligible for surgery needs to be completed to determine utilization rates, regional and national factors, and challenges in accessing care and to better understand what is happening to clients who do not elect surgery in terms of therapy and treatment received (i.e., use of orthotics, splints, adaptive devices, attendant care). With increasing demands on the health care system, there is a need to ensure that appropriate care and outcomes of treatment enable persons to reach their optimal level of functioning and independence.

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REFERENCES

1. Steeves JD, Lammertse D, Curt A, et al. Guidelines for the conduct of clinical trials for spinal cord injury (SCI) as developed by the ICCP panel: clinical trial outcome measures. *Spinal Cord.* 2007;45(3):206–221.
2. Snoek GJ, Ijzerman MJ, Hermens HJ, Maxwell D, Biering-Sorensen F. Survey of the needs of patients with spinal cord injury: impact and priority for improvement in hand function in tetraplegics. *Spinal Cord.* 2004;42(9):526–532.
3. Wuolle KS, Bryden AM, Peckham PH, Murray PK, Keith M. Satisfaction with upper-extremity surgery in individuals with tetraplegia. *Arch Phys Med Rehabil.* 2003;84(8):1145–1149.
4. Bryden AM, Sinnott KA, Mulcahey MJ. Innovative strategies for improving upper extremity function in tetraplegia and considerations in measuring functional outcomes. *Top Spinal Cord Inj Rehabil.* 2005;10(4):75–93.
5. Hanson RW, Franklin MR. Sexual loss in relation to other functional losses for spinal cord injured males. *Arch Phys Med Rehabil.* 1976;57(6):291–293.
6. Anderson KD. Targeting recovery: priorities of the spinal cord-injured population. *J Neurotrauma.* 2004;21(10):1371–1383.
7. Moberg E. Surgical treatment for absent single hand grip and elbow extension in quadriplegia. Principles and preliminary experience. *J Bone Joint Surg Am.* 1975;(57):196–206.
8. Hentz VR, Brown M, Keoshian LA. Upper limb reconstruction in quadriplegia: functional assessment and proposed treatment modifications. *J Hand Surg Am.* 1983;8(2):119–131.
9. Waters RL, Sie IH, Gellman H, Tognella M. Functional hand surgery following tetraplegia. *Arch Phys Med Rehabil.* 1996;77(1):86–94.
10. Gellman H, Sie I, Waters RL. Late complications of the weight-bearing upper extremity in the paraplegic patient. *Clin Orthop Relat Res.* 1988;(233):132–135.
11. Murphy CP, Chuinard RG. Management of the upper extremity in traumatic tetraplegia. *Hand Clin.* 1988;4(2):201–209.
12. McSweeney T. Discussion of Freehafer AA. Care of the hand in cervical spinal cord injuries. *Paraplegia.* 1969;(7):118–130.
13. Curtin CM, Gater DR, Chung KC. Upper extremity reconstruction in the tetraplegic population, a national epidemiologic study. *J Hand Surg Am.* 2005;30(1):94–99.
14. Harvey LA, Batty J, Jones R, Crosbie J. Hand function of C6 and C7 tetraplegics 1 - 16 years following injury. *Spinal Cord.* 2001;39(1):37–43.
15. Eng JJ, Teasell RW, Miller WC, et al. Spinal Cord Injury Rehabilitation Evidence: method of the SCIRE systematic review. *Top Spinal Cord Inj Rehabil.* 2007;13(1):1–10.
16. Downs SH, Black N. The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. *J Epidemiol Community Health.* 1998;52(6):377–384.
17. Strauss SE, Richardson WS, Glasziou P, Haynes RB. *Evidence-Based Medicine. How to Practice and Teach EBM.* 4th ed. Edinburgh: Churchill Livingstone; 2005.
18. Wright JG, Swiontkowski MF, Heckman JD. Introducing levels of evidence to the journal. *J Bone Joint Surg Am.* 2003;85-A(1):1–3.
19. Wright JG, Einhorn TA, Heckman JD. Grades of recommendation. *J Bone Joint Surg Am.* 2005;87(9):1909–1910.
20. Wright JG. Revised grades of recommendation for summaries or reviews of orthopaedic surgical studies. *J Bone Joint Surg Am.* 2006;88(5):1161–1162.
21. Rabischong E, Benoit P, Benichou M, Allieu Y. Length-tension relationship of the posterior deltoid to triceps transfer in C6 tetraplegic patients. *Paraplegia.* 1993;31(1):33–39.
22. Freehafer AA, Kelly CM, Peckham PH. Tendon transfer for the restoration of upper limb function after a cervical spinal cord injury. *J Hand Surg Am.* 1984;9(6):887–893.
23. McDowell CL, Moberg EA, House JH. The second international conference on surgical rehabilitation of the upper limb in traumatic quadriplegia. *J Hand Surg.* 1986;(11A):604–608.
24. Forner-Cordero I, Mudarra-Garcia J, Forner-Valero JV, Vilar-de-la-Pena R. The role of upper limb surgery in tetraplegia. *Spinal Cord.* 2003;41(2):90–96.
25. House JH, Comadoll J, Dahl AL. One-stage key pinch and release with thumb carpal-metacarpal fusion in tetraplegia. *J Hand Surg Am.* 1992;17(3):530–538.
26. McCarthy CK, House JH, Van Heest A, Kawiecki JA, Dahl A, Hanson D. Intrinsic balancing in reconstruction of the tetraplegic

hand. *J Hand Surg Am.* 1997;22(4):596–604.
27. Waters R, Moore KR, Graboff SR, Paris K. Brachioradialis to flexor pollicis longus tendon transfer for active lateral pinch in the tetraplegic. *J Hand Surg Am.* 1985;10(3):385–391.
28. Lamb DW, Chan KM. Surgical reconstruction of the upper limb in traumatic tetraplegia. A review of 41 patients. *J Bone Joint Surg Br.* 1983;65(3):291–298.
29. Colyer RA, Kappelman B. Flexor pollicis longus tenodesis in tetraplegia at the sixth cervical level. A prospective evaluation of functional gain. *J Bone Joint Surg Am.* 1981;63(3):376–379.
30. Failla JM, Peimer CA, Sherwin FS. Brachioradialis transfer for digital palsy. *J Hand Surg Br.* 1990;15(3):312–316.
31. Gansel J, Waters R, Gellman H. Transfer of the pronator teres tendon to the tendons of the flexor digitorum profundus in tetraplegia. *J Bone Joint Surg Am.* 1990;72(3):427–432.
32. Meiners T, Abel R, Lindel K, Mesecke U. Improvements in activities of daily living following functional hand surgery for treatment of lesions to the cervical spinal cord: self-assessment by patients. *Spinal Cord.* 2002;40(11):574–580.
33. Kelly CM, Freehafer AA, Peckham PH, Stroh K. Postoperative results of opponensplasty and flexor tendon transfer in patients with spinal cord injuries. *J Hand Surg Am.* 1985;10(6 pt 1):890–894.
34. Lo IK, Turner R, Connolly S, Delaney G, Roth JH. The outcome of tendon transfers for C6-spared quadriplegics. *J Hand Surg Br.* 1998;23(2):156–161.
35. Rieser TV, Waters RL. Long-term follow-up of the Moberg key grip procedure. *J Hand Surg Am.* 1986;11(5):724–728.
36. Remy-Neris O, Milcamps J, Chikhi-Keromest R, Thevenon A, Bouttens D, Bouilland S. Improved kinematics of unrestrained arm raising in C5-C6 tetraplegic subjects after deltoid-to-triceps transfer. *Spinal Cord.* 2003;41(8):435–445.
37. Dunkerley AL, Ashburn A, Stack EL. Deltoid triceps transfer and functional independence of people with tetraplegia. *Spinal Cord.* 2000;38(7):435–441.
38. Lacey SH, Wilber RG, Peckham PH, Freehafer AA. The posterior deltoid to triceps transfer: a clinical and biomechanical assessment. *J Hand Surg Am.* 1986;11(4):542–547.
39. Raczka R, Braun R, Waters RL. Posterior deltoid-to-triceps transfer in quadriplegia. *Clin Orthop Rel Res.* 1984;(187):163–167.
40. Kuz JE, Van Heest AE, House JH. Biceps-to-triceps transfer in tetraplegic patients: report of the medial routing technique and follow-up of three cases. *J Hand Surg Am.* 1999;24(1):161–172.
41. Revol M, Briand E, Servant JM. Biceps-to-triceps transfer in tetraplegia. The medial route. *J Hand Surg Br.* 1999;24(2):235–237.
42. Mulcahey MJ, Lutz C, Kozin SH, Betz RR. Prospective evaluation of biceps to triceps and deltoid to triceps for elbow extension in tetraplegia. *J Hand Surg Am.* 2003;28(6):964–971.
43. Rothwell AG, Sinnott KA, Mohammed KD, Dunn JA, Sinclair SW. Upper limb surgery for tetraplegia: a 10-year re-review of hand function. *J Hand Surg Am.* 2003;28(3):489–497.
44. Ejeskar A, Dahllof A. Results of reconstructive surgery in the upper limb of tetraplegic patients. *Paraplegia.* 1988;26(3):204–208.
45. Welraeds D, Ismail AA, Parent A. Functional reconstruction of the upper extremity in tetraplegia. Application of Moberg's and Allieu's procedures. *Acta Orthop Belg.* 2003;69(6):537–545.
46. Freehafer AA, Kelly CM, Peckham PH. Tendon transfer for the restoration of upper limb function after a cervical spinal cord injury. *J Hand Surg Am.* 1984;9(6):887–893.
47. Curtin CM, Hayward RA, Kim HM, Gater DR, Chung KC. Physician perceptions of upper extremity reconstruction for the person with tetraplegia. *J Hand Surg Am.* 2005;30(1):87–93.
48. Tuszynski MH, Steeves JD, Fawcett JW, et al. Guidelines for the conduct of clinical trials for spinal cord injury as developed by the ICCP panel: clinical trial inclusion/exclusion criteria and ethics. *Spinal Cord.* 2007;45(3):222–231.
49. Lammertse D, Tuszynski MH, Steeves JD, et al. Guidelines for the conduct of clinical trials for spinal cord injury as developed by the ICCP panel: clinical trial design. *Spinal Cord.* 2007;45(3):232–242.
50. Fawcett JW, Curt A, Steeves JD, et al. Guidelines for the conduct of clinical trials for spinal cord injury as developed by the ICCP panel: spontaneous recovery after spinal cord injury and statistical power needed for therapeutic clinical trials. *Spinal Cord.* 2007;45(3):190–205.

51. Fattal C. Motor capacities of upper limbs in tetraplegics: a new scale for the assessment of the results of functional surgery on upper limbs. *Spinal Cord.* 2004;42(2):80–90.
52. McColl MA, Paterson M, Davies D, Doubt L, Law M. Validity and community utility of the Canadian Occupational Performance Measure. *Can J Occup Ther.* 2000;67(1):22–30.
53. McColl MA, Law M, Baptiste S, Pollock N, Carswell A, Polatajko HJ. Targeted applications of the Canadian Occupational Performance Measure. *Can J Occup Ther.* 2005; 72(5):298–300.
54. Carswell A, McColl MA, Baptiste S, Law M, Polatajko H, Pollock N. The Canadian Occupational Performance Measure: a research and clinical literature review. *Can J Occup Ther.* 2004;71(4):210–222.
55. Law M, Polatajko H, Pollock N, McColl MA, Carswell A, Baptiste S. Pilot testing of the Canadian Occupational Performance Measure: clinical and measurement issues. *Can J Occup Ther.* 1994;61(4):191–197.
56. Law M, Baptiste S, McColl M, Opzoomer A, Polatajko H, Pollock N. The Canadian Occupational Performance Measure: an outcome measure for occupational therapy. *Can J Occup Ther.* 1990;57(2):82–87.
57. Sinnott KA, Dunn JA, Rothwell AG. Use of the ICF conceptual framework to interpret hand function outcomes following tendon transfer surgery for tetraplegia. *Spinal Cord.* 2004; 42(7):396–400.
58. Freehafer AA. Tendon transfers in tetraplegic patients: the Cleveland experience. *Spinal Cord.* 1998;36(5):315–319.
59. Mohammed KD, Rothwell AG, Sinclair SW, Willems SM, Bean AR. Upper-limb surgery for tetraplegia. *J Bone Joint Surg Br.* 1992;74(6): 873–879.