J Rehabil Med 2014; 46: 33–38

ORIGINAL REPORT

UPPER EXTREMITY RECONSTRUCTION IN NON-TRAUMATIC SPINAL CORD INJURIES: AN UNDER-RECOGNIZED OPPORTUNITY

Jan Fridén, MD, PhD[1,2], Carina Reinholdt, MD, PhD[1], Johanna Wangdell, OT, PhD[1] and Andreas Gohritz, MD[2]

From the [1]Department of Hand Surgery, Sahlgrenska University Hospital and Institute of Clinical Sciences, The Sahlgrenska Academy at University of Gothenburg, Gothenburg, Sweden and [2]Swiss Paraplegia Centre, Nottwil and Department of Plastic, Reconstructive and Aesthetic Surgery, Hand Surgery, Basel University Hospital, Basel, Switzerland

Objective: **This study reviews the usefulness of surgical improvement of arm and hand function in patients with non-traumatic spinal cord injury who differ significantly from individuals with post-traumatic tetraplegia with respect to age, injury pattern, gender and socio-economic factors.**

Design: **Case series. Tests were conducted preoperatively and 12 months postoperatively.**

Patients: The results of 14 upper extremity reconstructions in 11 patients (7 women, 4 men) with spinal cord injury, mean age at injury 49 years (standard deviation (SD) 12), were reviewed.

Methods: **Key pinch strength, grip strength and first web space opening were recorded pre- and post-operatively in all patients, 5 patients (7 hands) were evaluated prospectively regarding manual dexterity.**

Results: **All parameters were significantly improved. Strength of key pinch increased from 0.3 kg in 1 case and zero in 10 cases to a mean of 1.6 kg (SD 0.9). Mean grip strength increased from 0 to 3.2 kg (SD 4.5). Maximal distance between thumb and index increased from 2.1 cm (SD 4.1) to 6.4 cm (SD 4.4). Manual dexterity increased.**

Conclusion: **Individuals with stable non-traumatic tetraplegia benefit from surgical rehabilitation of their upper extremities. The number of non-traumatic spinal cord injuries is likely to increase as lifespan increases worldwide, and further research into the functional rehabilitation of this population will therefore become increasingly relevant.**

Key words: spinal cord injury; tetraplegia; non-traumatic; rehabilitation; upper extremity; tendon transfer.

J Rehabil Med 2014; 46: 33–38

Correspondence address: Jan Fridén, Department of Hand Surgery, Sahlgrenska University Hospital, SE-413 45 Gothneburg, Sweden. E-mail: jan.friden@orthop.gu.se

Accepted Jul 3, 2013; Epub ahead of print Nov 28, 2013

INTRODUCTION

Impaired upper extremity function is a highly disabling consequence of cervical spinal cord injury (SCI), rated above the loss of walking, sexual function and continence control by patients and care-givers alike (1, 2). Surgical improvement of elbow extension and grip function has the potential to enhance the independence and mobility of affected individuals, and considerably reduce the very high costs of treatment in approximately 70% of tetraplegic individuals (3–6). The safety and reliability of these techniques have been confirmed in numerous clinical series of patients affected by traumatic tetraplegia, mostly caused by traffic, sport or diving accidents (7–10). However, a considerable proportion of tetraplegia derives from non-traumatic (NT) sources, such as spinal canal stenosis, tumours, haemorrhage, ischaemia, viral or bacterial infections, skeletal disease and other causes (8, 11–14).

Surprisingly, almost no information can be found in the literature on the efficacy of tendon transfer and joint stabilization procedures in this group, which represents a considerable and increasing proportion of spinal-injured rehabilitation admissions. Furthermore, patients with NT SCI have quite different characteristics compared with the majority of the post-traumatic tetraplegia population regarding age and gender distribution, type of paralysis, life situation and socio-economic factors. These differences may influence patient selection, surgical methods, clinical outcome and patient satisfaction regarding such a reconstruction (8, 10–15). The aim of this study was to determine whether patients with NT cervical SCI may also benefit from surgical rehabilitation of their paralysed upper extremities.

MATERIAL AND METHODS

Patient demographics

This study included evaluations of 14 upper extremity reconstructions in 11 patients (7 women, 4 men) with mean age at injury of NT SCI of 49 years (standard deviation (SD) 12) (range 29–63 years). There were 10 tetraplegic patients and 1 walking patient with paralysis confined to her right hand. Incomplete injuries were seen in 6 cases. Arm and hand paralysis occurred due to intra-spinal tumours ($n=2$), ischaemia ($n=3$) or haemorrhage ($n=2$), 1 infection (Guillain-Barré syndrome), 1 syringomyelia with tethered cord syndrome and 2 unclear spinal cord damages without trauma. The mean time since the onset of tetraplegia due to NT SCI was 4.0 years (SD 5.7) (range 0.7–20 years). The International Classification (Table I) of the patients' upper extremity motor functions ranged from OCu0 to OCu8, 6 patients were categorized as exceptional paralysis pattern (IC group X) (Table II).

Table I. *International classification of surgery of the hand in tetraplegia*

Group	Spinal cord segment	Possible muscle transfers
0	≥C5	No transferable muscle below elbow
1	C5	Brachioradialis
2	C6	+ Extensor carpi radialis longus
3	C6	+ Extensor carpi radialis brevis
4	C6	+ Pronator teres
5	C7	+ Flexor carpi radialis
6	C7	+ Extensor digitorum
7	C7	+ Extensor pollicis longus
8	C8	+ Flexor digitorum
9	C8	No intrinsic had muscles
10 (X)		Exceptions

Measurements

Preoperative evaluation included sensory testing, measurements of joint range of motion and grading power of triceps and all muscles below the elbow to categorize each upper extremity. Key pinch strength (kg) was quantified by a Preston pinch gauge (Fabrication Enterprises Inc., White Plains, NY, USA). Grip strength (kg) was measured by Jamar Hand Dynamometer (North Coast Medical, Gilroy, USA), and the maximal distance between the thumb and index finger (cm) was measured using a ruler. Three of the patients (numbers 7–9) were operated before 2002, when measurements of key and grip strengths were performed using different methods. Therefore, these values are not included in the outcome data set. All patients were followed up routinely at 4 weeks, 6 months and 1 year post-operatively. Overall hand function could be evaluated prospectively in 5 individuals (7 hands) by Sollerman test consisting of 20 different tasks of daily living (15). Performance of each task ranges from 0 to 4 points according to the grip type used by the patient and the time necessary to complete it. A person with unimpaired hand function usually achieves a maximum of 80 points on the dominant and approximately 78 points on the non-dominant side. Most exercises are performed with one hand, and only a few bimanually, for example putting a clip on an envelope or using knife and fork. Thus, each side has to be tested separately, which allows better evaluation of improvement after surgery.

Table II. *Patient characteristics*

No	Gender	Origin of non-traumatic SCI	Age at injury, years	Time until first operation, years	Operation side	IC group[a]	Operations performed
1	M	Tumour	61	1.3	Right	OCu1	FPL split tenodesis, BR-FPL, CMC1 arthrodesis, EPL tenodesis
2	M	Tumour	63	7.3	Left	OCu8	BR-FPL, ECRL-FDP2-4, Zancolli Lasso, EDM-APB
3	F	Spinal haemorrhage	62	5.7	Right	OCuX	FPL split tenodesis, BR-FPL, EDM-APB
4	F	Thrombosis	34	0.7	Right	Ocu2	PD-T, FPL-radius, FPL split tenodesis, APL tenodesis
5	F	Infection/cervical myelitis (Guillain-Barré syndrome)	51	1.4	Bilateral	OCuX bilateral	Right: FPL split tenodesis, BR-FPL Left: FPL split tenodesis, BR-FPL, ECRL-FDP2-4, CMC1 arthrodesis, Zancolli Lasso
6	F	Thrombosis	29	1.3	Bilateral	OCu7	FPL split tenodesis, BR-FPL, ECRL-FDP2-4, FCU-FDS4+Zancolli Lasso
7	F	Spinal haemorrhage	56	1.2	Right	OCu8	FPL split tenodesis, EDM-APB
8	M	Unclear	51	1.5	Bilateral	OCu5	Left: FPL split tenodesis, BR-FPL, ECRL-FDP2-4, Zancolli Lasso Right: FPL split tenodesis, BR-FPL, ECRL-FDP2-4, Zancolli Lasso
9	F	Unclear	43	1.6	Right	Ocu3	BR-FPL, ECRL-FDP2-4
10	F	Thrombosis	44	2.3	Left	OcuX bilateral	FPL split tenodesis, CMC 1 arthrodesis, BR-FPL, ECRL-FDP2-4, EPL tenodesis, House intrinsic reconstruction, ECU tenodesis
11	M	Syringomelia/tethered cord syndrome	43	20	Bilateral	OcuX bilateral	FPL split tenodesis, CMC 1 arthrodesis, BR-FPL, ECRL-FDP2-4, EPL tenodesis, House intrinsic reconstruction, ECU tenodesis

[a]International classification system for surgery of the hand in tetraplegia (modified in Giens, 1984) (16), which denotes the number of muscles in the forearm under voluntary control with a minimum strength of grade 4 (MRC scale: 0 = no function to 5 = full function), indicating that the muscle can perform against some manual resistance.

SCI: spinal cord injury; IC: International Classification; O: (only) ocular afferent impulses in absence of tactile gnosis; OCu: oculo-cutaneous impulses (vision and tactile gnosis with a 2-point discrimination < 2410 mm in the thumb); APB: abductor pollicis brevis; APL: abductor pollicis longus; BR: brachioradialis; CMC1: carpometacarpal joint of thumb; ECRL: extensor carpi radialis longus; EDM: extensor digiti minimi; EIP: extensor indicis proprius; EPL: extensor pollicis longus; FCU: flexor carpi ulnaris; FDP: flexor digitorum profundus; FDS: flexor digitorum superficialis; FPL: flexor pollicis longus; MP: metacarpophalangeal.

Postoperative hand therapy

After-treatment included 2 training periods: the first started on the first postoperative day and focused on early mobilization of the flexion apparatus under splint protection to enable the patient to activate his or her new grip modus according to a specific scheme. Task-oriented training was introduced after 4 weeks, in parallel with functional training, and was targeted at integrating the new grip function into activities of daily living (5, 6).

Statistical methods

Group data are presented as mean (SD). Due to lack of Gaussian distribution of all parameters measured, the Wilcoxon matched-pairs sign rank test was applied to compare differences in preoperative and postoperative median values, respectively. A p-value less than 0.05 was considered significant.

RESULTS

There were 7 unilateral and 4 bilateral reconstructions performed in 15 upper extremities of 11 patients. One hand reconstruction was excluded because the follow-up time was less than 12 months. Surgical procedures included restoration of elbow extension by posterior deltoid-to-triceps transfer in 1 case, 1 passive key pinch by flexor pollicis longus (FPL)-tenodesis to the radius, active key pinch by brachioradialis (BR)-to-FPL transfer in 10 cases, restoration of global grasp by extensor carpi radialis longus (ECRL)-to-flexor digitorum profundus (FDP)2-4 transfer in 8 patients, activation of thumb abduction by EDM-to-APB transfer in 3 patients, distal thumb tenodesis in 10 patients, thumb CMC arthrodesis in 3 cases and intrinsic balancing using either the House or Zancolli plasty in 6 cases (Table II).

All parameters (key pinch and grip strength, opening of hand and manual dexterity) improved significantly ($p < 0.05$) after surgery and rehabilitation compared with preoperatively (Table III). Anti-gravity elbow extension graded M3+ was restored in one patient. The 2 clinical cases below detail some of the technical data for the surgery performed, together with functional and activity-related gains in daily living.

Case 1

A 62-year-old female patient, who was single and living alone, sustained a NT SCI due to a spontaneous spinal haemorrhage. Her right upper extremity was categorized as IC group OCu 2, and her left as group OCu 0. Functional reconstructive surgery was performed 5.7 years after her SCI on her right upper extremity including restoration of active key grip (BR-to-FPL), active thumb abduction (EDM-to-APB), thumb stabilization (FPL split tenodesis) and at a later stage reconstruction of active finger extension (PT-to-EDC). She achieved a key grip of 2.0 kg, a grip strength of 10.0 kg, and an increase in active thumb-index-opening by palmar thumb abduction from zero to 10 cm, her manual dexterity improved markedly, as measured by the Sollerman test, from 26 points preoperatively to 55 points postoperatively. Improvement occurred within 1 year following reconstruction.

Case 2

A 42-year-old man with severe neurological impairment in both arms and legs due to syringomyelia at C4 level and tethered spinal cord syndrome approximately 20 years ago, both his upper extremities were grouped OCuX. He underwent simultaneous restoration of active finger and thumb flexion, intrinsic hand function and passive finger and thumb extension in his left hand. His key pinch increased from zero to 3 kg. He was extremely satisfied with the result, especially because he had regained precision thumb-index-grip ability, which allowed him to manipulate his pills independently.

DISCUSSION

This study demonstrates that surgical reconstruction of hand and upper limb function after non-traumatic spinal cord injury with tetraplegia is beneficial. The timing of intervention does not seem to be a factor. In spite of the relatively high mean age of our patients, their overall key pinch strength of 2.1 kg (SD

Table III. *Outcome data*

	Key pinch strength (kg)		Grip strength (kg)		Distance thumb–index (cm)	
Patient	Preoperative	Postoperative	Preoperative	Postoperative	Preoperative	Postoperative
1	0.0	0.7	0.0	0.0	3.0	2.0
2	0.0	0.6	0.0	1.8	0.0	13.0
3	0.0	2.0	0.0	10.0	0.0	10.0
4	0.0	0.6	0.0	0.0	0.0	0.0
5	0.0	0.6	0.0	0.0	0.0	0.0
	0.0	1.1	0.0	1.2	0.0	5.0
6	0.0	1.4	0.0	1.0	13.0	14.0
	0.3	3.0	0.0	0.0	10.0	10.0
7	N/A	N/A	N/A	N/A	0.0	6.0
8	N/A	N/A	N/A	N/A	2.0	4.0
9	N/A	N/A	N/A	N/A	1.0	3.0
10	0.0	2.2	0.0	1.0	0.0	6.0
11	0.0	2.5	0.0	8.0	0.0	8.0
	0.0	3.0	0.0	12.0	0.0	8.0
Mean (standard deviation)	0.0 (0.1) (n=11)	1.6 (0.9) (n=11)	0 .0 (0) (n=11)	3.2 (4.5) (n=11)	2.1 (4.1) (n=14)	6.4 (4.4) (n=14)

0.87) corresponded very closely to the mean grip strength of 2 kg reported in a recent meta-analysis of 21 studies including 377 pinch reconstructions (17). Furthermore, clinical studies have demonstrated that training programmes can strengthen hand muscles of elderly individuals (18). Notably, the prospective Sollerman testing showed a marked increase in manual dexterity in all 5 prospectively tested individuals. Upper extremity function is, apart from the brain, the most important functional resource of tetraplegic patients and is judged to be the most desirable ability to regain after cervical SCI before bowel, bladder, sexual function, or walking ability (1). Restoration of elbow extension provides tetraplegic patients a larger hand work space and enables them to groom themselves, operate manual wheelchairs and drive cars. Improved hand function eliminates the need for adaptive equipment for eating, personal care, catheterizing, and many other activities of daily living (5–8). Surgical rehabilitation of arm and hand function is a powerful tool to enhance upper extremity function, and consequently autonomy and self-esteem, in tetraplegic patients, and allow them to regain meaningful roles and productive work.

Many case series have reviewed the outcomes of these procedures in patients with traumatic tetraplegia. In general, this group consists of young males injured by accidents in traffic or sports, violence or falls. Unfortunately, the NT SCI population appears to have been widely ignored despite its large population. NT aetiologies represent a significant proportion of the overall group of SCI, ranging from 20% to 52% in recent studies, while in older studies even higher rates and annual incidences of up to 8 per 100,000 rates were reported (7–10, 19). This study investigated the results of surgical rehabilitation of patients with lost upper extremity function due to NT SCI at the cervical level. Although it was a small series of 14 extremity reconstructions in 11 patients, it represents the only study targeted at this specific population. Moberg (20) in his classic monograph did not mention NT tetraplegia, while in their book Hentz & Leclercq (9) listed various types of NT SCI, yet did not give any single report of a reconstruction in such a patient. Researching the literature, we found 2 previous reports on functional surgery in NT tetraplegia. One patient operated in our unit (patient number 5) was mentioned in a series of flexor pollicis longus distal thumb tenodesis, but no details of the overall surgical concept and result of the bilateral reconstruction were given (21). Landi and co-workers (22) reported a highly exceptional case of a boy with incomplete paralysis after transverse myelitis in whom upper extremity surgery ultimately led to deterioration of his overall functional level. Various reasons may explain this paucity of data regarding functional restoration of upper extremity function in NT SCI. First of all, these techniques are in general greatly neglected. For example, less than 10% of appropriate candidates receive optimal treatment of their upper extremities according to an epidemiological study from the USA (23). The reasons for this underutilization of proven surgical techniques are varied and complex. After patients shift from acute care into long-term non-surgical care, our fractionated healthcare system is poor at transferring them back into the surgical realm for non-acute conditions (7).

Curtin and co-workers (24) suggested that "the biggest barrier to increased use of these procedures is the inadequate referral network between surgeons and physiatrists". Physiatrists who primarily care for these patients mostly have little exposure to tetraplegia surgery during their training and therefore lack adequate information to pass on their patients. Consequently, many patients are unaware that surgery is available to help them, or are saturated with medical intervention, and have inadequate support systems or poor perception of surgical outcomes (7). These barriers to transferral may be even higher in NT patients due to factors such as specific demographics, clinical presentation and rehabilitation outcomes, which influence the implications for management (25).

Overall, compared with traumatic SCI, individuals with NT SCI tend to be older, are more likely to be female, married and retired (8, 11). It can be speculated that, due to better social support, e.g. by spouse and family, the need for surgical rehabilitation may be rated lower in NT patients, compared with the individual with traumatic tetraplegia, who is 80% male, single, and most commonly in the age group ranging between the 2nd and 4th decade of life (12–14). It is possible for healthcare professionals to underestimate the rehabilitation potential of older adults, also as older patients have higher mortality and increased medical complication rates (26, 27). However, most investigations have not found a discernible relationship between age and functional independence after spinal cord injury (28–30), while some investigators have even suggested that older patients with cervical injuries may have a more favourable prognosis for functional outcome (29, 31). However, researchers have documented a substantially increasing incidence of tetraplegia, complete or incomplete, among patients aged over 45 years and more than 20% of all spinal cord injuries occur in persons who are 60 years or older (27–30). Although Moberg (20) stated "It is never too late. Age is not a contraindication, my oldest patients were over 60", few reports exist on the increasing number of patients of advanced age who seem to profit rarely from upper extremity reconstruction or may even be precluded due to age bias. Muscle force decreases by 15% per decade from the age of 50 to 70 years, resulting in a loss of motor neurones, motor units, muscle fibres and mass and interosseous and thenar muscle atrophy (28). Even decades after the spinal cord injury, most rewarding results of surgery were achieved in elderly patients, a subgroup which is certain to grow in the future (32).

Regarding the pattern of paralysis, various studies suggest that, compared with traumatic spinal cord lesions, NT SCI is more likely to be incomplete and is more likely to cause paraplegia than tetraplegia. Summarizing the results of 3 larger studies, 58–64% had incomplete paraplegia, 32–34% incomplete tetraplegia incomplete, 9–11% complete paraplegia complete, and 0–2 % complete tetraplegia (11–13, 33). Awareness of NT patients as potential surgical candidates may be low, as most published reports dealing with rehabilitation of the upper limb in tetraplegic patients have focused on complete traumatic injury of the cervical spinal cord. For example, the generally accepted International Classification of Functioning, Disability and Health system derives from observations of patients with American Spinal Injury Association (complete) lesions. A total of 7 of the extremities in our study were categorized as exceptional (group X) due to incomplete injury. Those patients, with a more complex functional loss often demonstrate various degrees of spasticity and muscle-joint rearrangements (10) requiring a more individualized approach than the algorithmic approach based on the International Classification in complete injury patients. Unfortunately, treatment decisions are less straightforward, because muscles lacking normal excitation parameters perform less reliably after transfer and, may not be so readily adapted to the patient with a severe, but still incomplete, lesion (34). The incompletely injured patient may more often need preoperative therapy or surgery to correct certain sequelae of the injury, above all joint contractures. In complete tetraplegia it is generally recommended to operate first on the arm with the greatest potential in order to make this the dominant one. Incompletely paralysed patients may present with one almost normal side and may be ambulant and functioning at a high level, showing a monoplegia-like pattern, and the value of surgery for their affected side may be questioned. On the other hand, by having an essentially normal arm, they are far less impaired by postoperative immobilization and rehabilitation than patients with complete injury, who might need to use a powered wheelchair during and beyond the postoperative period. Finally, there might not be the same level of motivation and dedication following surgery when the goal is only to improve somewhat the less important side. However, small improvements can also be experienced as great progress, such as in our monoplegic patient who showed greatly improved precision grip functions after restoration of palmar abduction and interphalangeal tenodesis of her right thumb (35).

In summary, while NT patients with incomplete cervical spinal cord injuries are challenging for the reconstructive surgeon, they benefit from individualized evaluation, planning and carefully executed operations.

In conclusion, individuals with stable NT SCI, although they differ from those with traumatic SCI regarding demography and injury patterns, can benefit in the same way as traumatic cases from surgical rehabilitation of their upper extremities. This study of patients with a loss of upper extremity function due to NT SCI reveals the wide spectrum of surgical techniques to restore basic arm and hand function (36), and indicates that selected individuals with NT spinal cord lesions may benefit from these operations in the same way as patients after traumatic paralysis.

ACKNOWLEDGEMENTS

This work was supported by the Swedish Research Council Grant 11200, Sahlgrenska University Hospital and University of Gothenburg.

REFERENCES

1. Anderson, KD. Targeting recovery: priorities of the SCI population. J Neurotrauma 2004; 21: 1371–1383.
2. Anderson KD, Fridén J, Lieber RL. Acceptable benefits and risks associated with surgically improving arm function in individuals living with cervical spinal cord injury. Spinal Cord 2009; 47: 334–338.
3. Fridén J, editor. Tendon transfers in reconstructive hand surgery. Oxford: Taylor & Francis; 2005.
4. Fridén J, Gohritz A. Novel concepts integrated in neuromuscular assessments for surgical restoration of arm and hand function in tetraplegia. Phys Med Rehabil Clin N Am 2012; 23: 33–50.
5. Wangdell J, Fridén J. Satisfaction and performance in patient selected goals after grip reconstruction in tetraplegia. J Hand Surg Eur 2010; 35: 563–568.
6. Wangdell J, Fridén J. Performance of prioritized activities is not correlated with functional factors after grip reconstruction in tetraplegia. J Rehabil Med 2011; 43: 626–630.
7. Zlotolow DA. The role of the upper extremity surgeon in the management of tetraplegia. J Hand Surg 2011; 36A: 929–935.
8. McKinley WO, Seel RT, Hardman JT. Nontraumatic spinal cord injury: incidence, epidemiology, and functional outcome. Arch Phys Med Rehabil 1999; 80: 619–623.
9. Hentz VR, Leclercq C, editors. Surgical rehabilitation of the upper limb in tetraplegia. Philadelphia: WB Saunders; 2002.
10. Fridén J, Reinholdt C. Current concepts in reconstruction of hand function in tetraplegia. Scand J Surg 2008; 97: 341–346.
11. McKinley WO, Seel RT, Gadi RK, Tewksbury MA. Non-traumatic versus traumatic spinal cord injury: a rehabilitation outcome comparison. Am J Phys Med Rehabil 2001; 80: 693–699.
12. New PW, Rawicki HB, Bailey MJ. Non-traumatic spinal cord injury: demographic characteristics and complications. Arch Phys Med Rehabil 2002; 83: 996–1001.
13. New PW. Functional outcomes and disability after non-traumatic spinal cord injury rehabilitation: results from a retrospective study. Arch Phys Med Rehabil 2004; 86: 250–261.
14. Gupta A, Taly AB, Srivastava A, Murali T. Non-traumatic spinal cord lesions: epidemiology, complications, neurological and functional outcome of rehabilitation. Spinal Cord. 2009; 47: 307–311.
15. Sollerman C, Ejeskär A. Sollerman hand function test. Scand J Plast Reconstr Surg 1995; 29: 167–176.
16. McDowell C, Moberg EA, House JH. The Second International Conference on Surgical Rehabilitation of the Upper Limb in Tetraplegia (Quadriplegia). J Hand Surg 1986; 604–608.
17. Hamou C, Shah NR, Di Ponio L, Curtin CM. Pinch and elbow extension restoration in people with tetraplegia: a systematic review of the literature. J Hand Surg Am 2009; 34: 692–699.
18. Keen DA, Yue GH, Enoka RM. Training-related enhancement in the control of motor output in elderly humans. J Appl Physiol 1994; 77: 2648–2658.
19. Kurtzke JF. Epidemiology of spinal cord lesion. Exp Neurol 1975; 48: 163–236.
20. Moberg E. The upper limb in tetraplegia. A new approach to surgical rehabilitation. Stuttgart: Thieme; 1979.
21. Ejeskär A, Dahlgren A, Fridén J. Split distal flexor pollicis longus tenodesis: long-term results. Scand J Plast Reconstr Surg Hand Surg 2002; 36: 96–99.
22. Landi A, Mulcahey MJ, Caserta G, Della Rosa N. Tetraplegia: update on assessment. Hand Clin 2002; 18: 377–389.
23. Curtin CM, Gater DR, Chung KC. Upper extremity reconstruction in the tetraplegic population, a national epidemiologic study. J Hand Surg 2005; 30A: 94–99.
24. Curtin CM, Wagner JP, Gater DR, Chung KC. Opinions on the treatment of people with tetraplegia: contrasting perceptions of physiatrists and hand surgeons. J Spinal Cord Med 2007; 30: 256–362.
25. Dunn JA, Hay-Smith EJ, Whitehead LC, Keeling S. Issues influencing the decision to have upper limb surgery for people with tetraplegia. Spinal Cord. 2012; 50: 844–847.
26. DeVivo MJ, Kartus PL, Rutt RD, Stover SL, Fine PR. The influence of age at time of spinal cord injury on rehabilitation outcome. Arch Neurol 1990; 47: 687–691.
27. Roth EJ, Lovell L, Heinemann AW, Lee MY, Yarkony GM. The

older adult with a spinal cord injury. Paraplegia 1992; 30: 520–526.
28. Alander DH, Andreychik DA, Stauffer ES. Early outcome in cervical spinal cord injured patients older than 50 years of age. Spine 1994; 19: 2299–2301.
29. Pentland W, McColl MA, Rosenthal C. The effect of aging and duration of disability on long term health outcomes following spinal cord injury. Paraplegia 1995; 33: 367–373.
30. Kiwerski JE. Injuries to the spinal cord in elderly patients. Injury 1992; 23: 397–400.
31. Buckwalter JA, Woo SL, Goldberg VM, Hadley EC, Booth F, Oegema TR, et al. Soft tissue aging and muskulo-skeletal function. J Bone Joint Surg 1993; 75: 1533–1548.
32. Fridén J, Gohritz A, Ejeskär A. Upper limb surgery in tetraplegic patients over 60 years – you are never too old to improve. Abstract 308. Proceedings of the International Meeting on Upper Limb in Tetraplegia, Philadelphia, PA. September 17–20, 2007.
33. Schönherr MC, Groothoff JW, Mulder GA, Eisma WH. Functional outcome of patients with spinal cord injury: rehabilitation outcome study. Clin Rehabil 1999; 13: 457–463.
34. Hentz VR, Leclercq C. The management of the upper limb in incomplete lesions of the cervical spinal cord. Hand Clin 2008; 24: 175–184.
35. Fridén J, Gohritz A, Turcsányii I, Ejeskär A. Restoration of active palmar abduction of the thumb in tetraplegia by tendon transfer of the extensor digiti minimi to abductor pollicis brevis. J Hand Surg (Eur) 2012; 37: 665–672.
36. Fridén J, Reinholdt C, Turcsányii I, Gohritz A. A single-stage operation for reconstruction of hand flexion, extension, and intrinsic function in tetraplegia: the alphabet procedure. Tech Hand Up Extrem Surg 2011; 15: 230–235.