Upper Limb Rehabilitation Following Spinal Cord Injury

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Key Points

Neuromuscular stimulation-assisted exercise following a SCI is effective in improving muscle strength, preventing injury and increasing independence in all phases of rehabilitation.

Augmented feedback does not improve motor function of the upper extremity in SCI rehabilitation patients.

Intrathecal baclofen may be an effective intervention for upper extremity hypertonia of spinal cord origin.

Afferent inputs in the form of sensory stimulation associated with repetitive movement and peripheral nerve stimulation may induce beneficial cortical neuroplasticity required for improvement in upper extremity function.

Restorative therapy interventions need to be associated with meaningful change in functional motor performance and incorporate technology that is available in the clinic and at home.

The use of concomitant auricular and electrical acupuncture therapies when implemented early in acute spinal cord injured persons may contribute to neurologic and functional recoveries in spinal cord injured individuals with AIS A and B.

There is clinical and intuitive support for the use of splinting for the prevention of joint problems and promotion of function for the tetraplegic hand; however, there is very little research evidence to validate its overall effectiveness.

Shoulder exercise and stretching protocol reduces post SCI shoulder pain intensity.

Acupuncture and Trager therapy may reduce post-SCI upper limb pain.

Prevention of upper limb injury and subsequent pain is critical.

Reconstructive surgery appears to improve pinch, grip and elbow extension functions that improve both ADL performance and quality of life in tetraplegia.

Nerve transfer surgery to restore hand and upper limb function in the person with tetraplegia is emerging as another surgical alternative.

The use of neuroprostheses appears to have a positive impact on pinch and grip strength and ADL functions in C5-C6 complete tetraplegia, however, access to the devices are limited and continue to be expensive in use.

The IST-12 neuroprosthesis, a second generation, myoelectrically controlled implantable device appears to have a positive effect on pinch and grasp functions which result in increased independence with activities of daily living.
Table of Contents

Abbreviations ........................................................................................................................................... i

1.0 Introduction ........................................................................................................................................ 1

2.0 Acute Phase of Rehabilitation ......................................................................................................... 3
  2.1 Exercise and Strengthening ............................................................................................................. 3

3.0 Augmented Feedback on Motor Functions ....................................................................................... 7

4.0 Pharmacological Interventions ........................................................................................................ 10

5.0 Restorative Strategies ...................................................................................................................... 12
  5.1 Plasticity of Motor Systems ............................................................................................................. 12
  5.2 Complementary Alternative Therapies ......................................................................................... 16
  5.3 Splinting ....................................................................................................................................... 17

6.0 Subacute Phase of Rehabilitation .................................................................................................. 19
  6.1 Upper Limb Injuries ....................................................................................................................... 19
    6.1.1 Shoulder Injuries ..................................................................................................................... 20
    6.1.2 Elbow/Wrist and Hand Injuries .............................................................................................. 21
  6.2 Lower Limb Injuries ....................................................................................................................... 21

7.0 Reconstructive Surgery and Tendon Transfer ............................................................................... 25
  7.1 Hand ............................................................................................................................................. 25
  7.2 Elbow Extension ............................................................................................................................ 33
    7.2.1 Posterior Deltoid to Triceps ................................................................................................. 33
    7.2.2 Biceps to Triceps ............................................................................................................... 35
  7.3 Multiple Reconstructions .............................................................................................................. 36

8.0 Nerve Transfers .............................................................................................................................. 41
  8.1 Fundamental Principles .................................................................................................................. 41
  8.2 Advantages over Tendon Transfers ............................................................................................. 42
  8.3 Potential Drawbacks of Nerve Transfers .................................................................................... 43
  8.4 Assessment and Surgical Timing .................................................................................................. 43
  8.5 Evidence ....................................................................................................................................... 43

9.0 Neuroprostheses .............................................................................................................................. 44
  9.1 Types of Neuroprostheses ............................................................................................................ 45
    9.1.1 Freehand System .................................................................................................................... 45
    9.1.2 NESS H200 (formerly HandMaster-NMS-1) ....................................................................... 52
    9.1.3 Bionic Glove ......................................................................................................................... 53
    9.1.4 ETHZ-ParaCare System ....................................................................................................... 55
    9.1.5 Stimulus Router System ....................................................................................................... 55

  9.2 Other Surface or Percutaneous Neuroprostheses Systems .......................................................... 56
    9.2.1 NEC-FES System ................................................................................................................ 56
    9.2.2 Rebersek and Vodovik (1973) Neuroprosthesis ................................................................... 56
    9.2.3 Belgrade Grasping-Reaching System ............................................................................... 56

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<table>
<thead>
<tr>
<th>Abbreviations</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AbINT</td>
<td>Activity based Intervention</td>
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<tr>
<td>ADL</td>
<td>Activities of Daily Living</td>
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<td>AIS</td>
<td>ASIA Impairment Scale</td>
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<tr>
<td>AP</td>
<td>Action Potential</td>
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<td>APB</td>
<td>Abductor Pollicis Brevis</td>
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<tr>
<td>BGS</td>
<td>Belgrade Grasping-Reaching System</td>
</tr>
<tr>
<td>BR</td>
<td>Brachioradialis</td>
</tr>
<tr>
<td>CAM</td>
<td>Complementary Alternative Therapies</td>
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<tr>
<td>CHART</td>
<td>Craig Handicapped Assessment and Reporting Tools</td>
</tr>
<tr>
<td>CNS</td>
<td>Central Nervous System</td>
</tr>
<tr>
<td>COPM</td>
<td>Canadian Occupational Performance Measure</td>
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<tr>
<td>CPG</td>
<td>Central Pattern Generators</td>
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<tr>
<td>CSF</td>
<td>Cerebrospinal Fluid</td>
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<tr>
<td>Cu-</td>
<td>Cutaneous</td>
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<tr>
<td>CWRU</td>
<td>Case Western Reserve University</td>
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<tr>
<td>ECRB</td>
<td>Extensor Capri Radialis Brevis</td>
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<tr>
<td>ECRL</td>
<td>Extensor Capri Radialis Longus</td>
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<tr>
<td>EDM</td>
<td>Extensor Digiti Minimi</td>
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<tr>
<td>EMG</td>
<td>Electromyography</td>
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<tr>
<td>FCR</td>
<td>Flexor Carpi Radialis</td>
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<tr>
<td>FDP</td>
<td>Flexor Digitorum Profundus</td>
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<tr>
<td>FES</td>
<td>Functional Electrical Stimulation</td>
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<tr>
<td>FEV-1</td>
<td>Forced Expiratory Flow</td>
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<td>FIM</td>
<td>Functional Independence Measure</td>
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<tr>
<td>fMRI</td>
<td>Functional Magnetic Resonance Imaging</td>
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<td>FNS</td>
<td>Functional Neurostimulation</td>
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<td>FPL</td>
<td>Flexor Pollicis Longus</td>
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<td>FVC</td>
<td>Forced Vital Capacity</td>
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<td>GRT</td>
<td>Grasp and Release Test</td>
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<td>HHD</td>
<td>Handheld Dynamometry</td>
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<tr>
<td>IST-12</td>
<td>Implanted Stimulator-Telemeter</td>
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<tr>
<td>MeCFES</td>
<td>Myoelectrically Controlled Functional Electrical Stimulation</td>
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<td>MP</td>
<td>Massed Practice</td>
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<td>MRCS</td>
<td>Medical Research Council Scale</td>
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<tr>
<td>MRI</td>
<td>Magnetic Resonance Imaging</td>
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<tr>
<td>NMS</td>
<td>Neuromuscular Stimulation</td>
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<tr>
<td>NP</td>
<td>Neuroprosthesis</td>
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<tr>
<td>NRS</td>
<td>Numeric Rating Scale</td>
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<tr>
<td>O-</td>
<td>Ocular</td>
</tr>
<tr>
<td>OT</td>
<td>Occupational Therapy</td>
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<tr>
<td>PC</td>
<td>Performance Corrected</td>
</tr>
<tr>
<td>PD</td>
<td>Posterior third of the deltoid</td>
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<tr>
<td>PET</td>
<td>Positron Emission Topography</td>
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<td>PO</td>
<td>Power Output</td>
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<td>PT</td>
<td>Physiotherapy</td>
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<tr>
<td>PT</td>
<td>Pronator Teres</td>
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<tr>
<td>PVA</td>
<td>Paralyzed Veterans of America</td>
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<tr>
<td>QIF</td>
<td>Quadriplegic Index Function</td>
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<tr>
<td>REL</td>
<td>Rehabilitation Engineering Laboratory Hand Function Test</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------</td>
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</tr>
<tr>
<td>ROM</td>
<td>Range of Motion</td>
</tr>
<tr>
<td>rTMS</td>
<td>Repetitive Transcranial Magnetic Stimulation</td>
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<tr>
<td>SCI</td>
<td>Spinal Cord Injury</td>
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<tr>
<td>SCIM</td>
<td>Spinal Cord Independence Measure</td>
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<tr>
<td>SEM</td>
<td>Standard Error of Mean</td>
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<tr>
<td>SRS</td>
<td>Stimulator Router System</td>
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<tr>
<td>SS</td>
<td>Somatosensory Peripheral Nerve Stimulation</td>
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<tr>
<td>VRS</td>
<td>Verbal Rating Scale</td>
</tr>
<tr>
<td>WUSPI</td>
<td>Wheelchair Users Shoulder Pain Index</td>
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</table>
Upper Limb Rehabilitation Following Spinal Cord Injury

1.0 Introduction

Raineteau and Schwab (2001) defined a spinal cord injury (SCI) as a lesion within the spinal cord that results in the disruption of nerve fibre bundles that convey ascending sensory and descending motor information. A SCI at the cervical level results in tetraplegia, the loss of hand and upper limb function with impairment of motor and/or sensory function. In incomplete spinal cord injuries, some neural transmission can still pass through the spinal cord, but it is often fragmentary or distorted which leads to additional neurological complications such as chronic pain or spasticity. Tetraplegia results in impairment of function in the arms, as well as in the trunk, legs and pelvic organs. It is estimated that cervical SCI accounts for approximately 50% of all people living with SCI (Steeves et al. 2007). 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. The use of the upper extremities is critical in completing basic activities of daily living (ADL) such as self-feeding, 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 using their arms (Snoek et al. 2004). The level at which the injury or lesion occurs and the completeness of the lesion (incomplete or complete) indicate the level of independence of the person (Ditunno 1999).

The Paralyzed Veterans of America (PVA) have published a clinical practice guideline, “Outcomes Following Traumatic Spinal Cord Injury: Clinical Practice Guidelines for Health Care Professionals,” that outlines the expected skills and outcomes that a person is expected to acquire and achieve at each significant level of injury (Consortium for Spinal Cord Medicine 1999). As medical care of the spinal cord injured person has improved, life expectancy now approaches the rest of the population. Secondary complications from SCI and aging are ongoing challenges and include pain, contractures and upper limb musculoskeletal injuries (Sipski & Richards 2006).

Hanson and Franklin (1976) compared sexual function to three other impairments in patients with SCI; approximately 76% of the subjects gave the highest priority to upper extremity function. Snoek et al. (2004) surveyed the needs of patients with SCI and found a high impact and high priority for improvement in hand function in those with tetraplegia comparable to that for bladder and bowel dysfunction. A recent study by Anderson (2004) found similar results 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, Anderson (2004) reported that 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 post SCI. Anderson (2004) reported that recovering even partial arm and hand function may have a significant impact on independence.

Given the above, the initial care, management, rehabilitation and prevention of injuries in the upper limb of those with tetraplegia are of great importance in maximizing and maintaining independence. Management of the tetraplegic upper limb tends to be eclectic involving traditional rehabilitation interventions of task directed training in which clients perform many repetitions of movements relevant to ADL, use of orthosis (splints and adaptive devices) and upper extremity surgery. According to Murphy and Chuinard (1998), management and care of
the upper limb can be divided into three phases: the acute, the subacute and the reconstructive phase. Bryden et al. (2005) proposed a similar hierarchy of upper extremity functional restoration for individuals with tetraplegia. This includes the provision of conservative treatment methods followed by surgical restoration using residual motor functions and increasing or augmenting voluntary functions with functional electrical stimulation (FES) for maximal upper limb function. The aims of the first two phases of rehabilitation are to prevent complications, to achieve optimal functioning within the limits of the neurological deficit, and to create optimal conditions for the reconstructive phase (Bedbrook 1981; Curtin 1994; Harvey 1996; Keith & Lacey 1991). In the latter phase, various surgical options and FES are available to improve positioning and stabilization of the arm as well as key and palmar grasp function (Johnstone et al. 1988; Peckham et al. 2001; Snoek et al. 2000; Triolo et al. 1996; Waters et al. 1996). The new clinical practice guidelines by the Consortium for Spinal Cord Medicine (2005) emphasize the prevention of upper limb injuries among individuals with tetraplegia to maintain independence.

Although there is no overall consensus regarding the management of the tetraplegic upper limb, Hummel et al. (2005), Snoek et al. (2005) and the Consortium for Spinal Cord Medicine (2005) provide excellent discussions and recommendations.

There is agreement that restoration of hand function is an important goal in rehabilitation. It is also worth noting that there are very few upper extremity tests that accurately evaluate upper limb function in this population (van Tuijl et al. 2002). Curtin (1994) and Krajnik and Bridle (1992) noted a great inconsistency in evaluation and documentation of the tetraplegic upper limb between therapists.

Several studies have explored increased hand function as a result of reconstructive surgery and/or neuroprosthesis. Although these, and many other treatment options exist, have proven to improve the overall functioning and functional independence of the person with tetraplegia, clinical practice has shown that suitable candidates for reconstructive surgery or FES interventions often do not accept the treatment that is offered (Snoek et al. 2004). According to Moberg (1975), over 60% of the tetraplegic population could benefit from reconstructive surgery and it continues to be widely advocated (Snoek et al. 2004). Curtin et al. (2005) reported in their study that reconstructive surgery is underutilized in this population reporting that fewer than 10% of persons with tetraplegia actually undergo surgical reconstruction. Reconstructive surgeries such as muscle/tendon transpositions of the intact arm or hand muscles are designed to substitute for lost motor function (van Tuijl et al. 2002). Despite this, controversy still exists among clinicians as to whether or not to perform reconstructive surgeries and the benefits of reconstructive surgery have not been clarified with good quality randomized clinical trials (Harvey et al. 2001). Gorman et al. (1997) deduced that 11% of the tetraplegic population could be candidates for an implanted FES device (Freehand System). Most implanted FES devices are usually combined with augmentative and substitutional reconstructive surgery (Keith et al. 1996).

The main focus in rehabilitation of the spinal cord injured person is compensation of functional loss and using those parts of the sensorimotor system, which are still intact (van Tuijl et al. 2002). Research findings regarding neuroplasticity and neurological recovery of the spinal cord also include current rehabilitation practices that focus on strategies to restore function lost after SCI as significant recovery of function is observed after incomplete and even complete SCI (Beekhuizen 2005; Bradbury et al. 2002; Buchuli & Schwab 2005; Curt et al. 2008; Kirshblum et al. 2004; Marino et al. 1999; Waters et al. 1994). There is emerging evidence demonstrating and highlighting the importance of understanding the motor control strategies that the central
nervous system (CNS) uses to govern hand movements in abled individuals. This information may be useful in guiding the rehabilitation process after cervical SCI and ensuring that the exercises performed for the hand and upper limb are effective for restoring functional ability (Backus 2010). The literature is reporting on the presence of muscle synergies that are a motor control paradigm that is being actively investigated (Bizzi et al. 2008; Cheung et al. 2005; d’Avella et al. 2003; Overduin et al. 2008).

This body of research puts forth the theory that there is a modular approach to motor control, where the CNS activates predefined combinations of muscles, rather than explicitly controlling individual muscles (Zariffa et al. 2012a). This could have implications in neurorehabilitation treatment implementation where there is explicit retraining of muscle synergies that are known to be useful in the able-bodied population. It is that functional performance might be improved across a broad range of tasks (Zariffa et al. 2012a). To date most of the muscle synergy studies have explored the arm with a limited number of studied investigating the existence of muscle synergies in the hand (Zariffa et al. 2012a). Zariffa et al. (2012a) investigated if there any synergies present in able-bodied individuals while using different types of hand grips relevant to ADLs such as pulp to pulp pinch, cylindrical grasp and lateral key pinch and attempted to determine whether the presence or absence of these synergies after SCI is correlated with functional abilities. There were several time-invariant synergies observed to occur consistently in a substantial proportion of able-bodied subjects and in the SCI population there was evidence that similar synergies existed but in different proportions and no clear relationship was found between the functional abilities of subjects with SCI and those subjects deviation from able-bodied synergy patterns. Further, Zariffa et al. (2012a) found that the most common synergy in the able-bodied population was EDC and EIP for finger extension and FDS and FCU for wrist flexion used to position the hand during grasping activities. In SCI the most common synergy was FCR and ECR for stabilizing the wrist and DII and TEMG for independent thumb movement (Latash et al. 2010; Santello et al. 1998; Weiss et al. 2004). Further research and investigation is required to determine how this information can be transferred into the treatment of the hand and upper limb of the SCI injured person for improving functional task performance.

2.0 Acute Phase of Rehabilitation

Rehabilitation and management of the person with a SCI requires an interdisciplinary team approach during the acute phase of rehabilitation. The level and classification of the injury is determined and the goals of maintaining range of motion (ROM), improving strength, managing tone, spasticity, and the prevention of secondary complications in order to achieve the person’s maximum functional ability for independent transfers, ADL and mobility are developed (Drolet et al. 1999; Haisma et al. 2006; Sipski & Richards 2006). Clinicians must be knowledgeable about the change in physical capacity based on level of injury as a prerequisite to developing optimal rehabilitation programs and for setting realistic individual rehabilitation goals.

2.1 Exercise and Strengthening

In the acute phase of rehabilitation, the person with a SCI has a reduced physical capacity because of muscle weakness, loss of autonomic control below the level of injury, reduced activity and subsequent changes in metabolic and vascular function (Haisma et al. 2006). The inability to reach one’s maximum potential will result in an increased risk of medical and secondary complications and has been correlated to a reduced level of functioning and quality of life. One of the important goals of rehabilitation is to reverse the debilitative cycle of reduced physical capacity that leads to reduced activity and functioning (Haisma et al. 2006). With shorter hospital lengths of stay, individuals with a SCI have fewer training opportunities. It is
important to determine whether people with SCI can maintain their levels of physical capacity after discharge.

There are very few evidence-based analyses of the effectiveness of specific exercise therapies (Sipski & Richards 2006). Most research has only focused on one component of physical capacity (e.g., peak oxygen uptake [VO2 peak], or muscle strength, or respiratory function).

Many physical factors have been associated with optimal functional independence individual post-SCI and muscle strength is identified as an important contributor to functional independence (Drolet et al. 1999). Studies by Noreau et al. (1993), Marcil et al. (1995) and Durand et al. (1996) all noted a correlation between the level of the lesion, performance in functional abilities in relationship to peak oxygen intake and level of muscle strength. These associations were significant in individuals with tetraplegia especially in areas of sitting balance, spasticity of the lower limb, hand-grip strength, wrist extensor strength and global upper extremity strength. These functional areas have also been related to Functional Independence Measure (FIM) motor and self-care scores. It was also identified that upper extremity strength must be adequate to support the body weight during transfers and lower limb strength for walking. Optimal recovery of muscle strength following a SCI is an essential objective of functional rehabilitation of individuals with a SCI (Drolet et al. 1999).

Changes in motor function observed six months after an injury may be partially explained by collateral sprouting within the spinal cord (Mange et al. 1990). Changes between 2 and 8 months may be related to peripheral nerve sprouting and muscle fiber hypertrophy after partial denervation (Mange et al. 1990; Yang et al. 1990). Natural muscle strength recovery may occur up to two years post injury, with the recovery rate being more important for the first six months as measured by manual muscle testing (Ditunno et al. 1992; Mange et al. 1992; Waters et al. 1993). Muscle strength gains have been attributed to two different mechanisms in healthy subjects. In healthy subjects, short-term gains (2-4 weeks) might be explained by improved capacity to recruit motor units (neural adaptation) and gains observed after 4 weeks have been attributed to morphological changes within the contractile tissue inducing muscle fiber hypertrophy (Sale 1988). Additional studies regarding cardiovascular and exercise interventions are discussed in the Cardiovascular chapter and Physical Activity chapter.

**Table 1 Exercise and Strengthening**

<table>
<thead>
<tr>
<th>Author Year Country Score Research Design Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
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<tr>
<td>Needham-Shrophire et al. 1997 USA/CA PEDro=8 RCT N_initial=43; N_final=32</td>
<td>Population: Age=18-45 yr; Gender: males=31, females=3; Level of injury: tetraplegia; Time since injury=3 yr. Treatment: Subjects randomly assigned to one of three groups: Group 1 – received 8 wk of neuromuscular stimulation (NMS) assisted arm ergometry exercise; Group 2 – received 4 wk of NMS assisted exercise, then 4 wk of voluntary arm crank exercise; Group 3 (control group) – voluntary exercise for 8 wk without the application on NMS. Outcome Measures: Manual muscle test.</td>
<td>1. No significant difference was found at the 4-week evaluation between Groups 1 and 2 (p=0.22) or between Groups 2 and 3 (p=0.07). 2. Subjects in Group 1 had a higher proportion of muscles improving one or more muscle grades after 4 weeks of NMS cycling compared with Group 3 (p&lt;0.003). 3. Following the second 4 weeks of training, a significant difference was found between Groups 1 and 3 (p&lt;0.0005) and between Groups 2 and 3 (p&lt;0.03). 4. No statistical difference was found</td>
</tr>
<tr>
<td>Author, Year, Country</td>
<td>Score</td>
<td>Research Design</td>
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<td>-----------------------</td>
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<tr>
<td>Hicks et al. 2003, Canada</td>
<td>PEDro=5</td>
<td>RCT</td>
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<tr>
<td>Drolet et al. 1999, Canada</td>
<td>Pre-post</td>
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<tr>
<td>Haisma et al. 2006, Netherlands</td>
<td>Observational</td>
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</table>
Cameron et al. 1998  
USA  
Case Series  
N=11  

**Population:** Age=18-45 yr; Gender: males=10, females=1; Level of injury: C4-C7; Time since injury >1yr post injury.  
**Treatment:** Testing of hybrid device, 8 wk of Neuromuscular Stimulation (NMS) assisted exercise with training sessions 3x/wk.  
**Outcome Measures:** Manual muscle test scores biceps, triceps, wrist flexors and extensors.

4. Those with a complete lesion had greater HHD score and lower % of FVC than those with incomplete lesions (p<0.05).

1. All subjects showed improvement in one or more of their manual muscle scores with the most dramatic occurring in the tricep muscle group (average increase 1.1 +/- 0.2 for L triceps, 0.7 +/- 0.1 for R).  
2. Results show NMS in combination with resistive exercise can be used safely and assists in the strengthening of voluntary contractions.

**Discussion**

The five studies presented address the long-term change of upper limb strength after the spinal cord injured person has returned to community living. Needham-Shophire et al. (1997) found that Neuromuscular stimulation (NMS)-assisted exercise ergometry alone and in combination with voluntary arm crank exercise was effective for strengthening of the upper limb for SCI injured individuals well after injury (mean time since injury 3 years).  

Hicks et al. (2003) demonstrated all study participants had progressive increases in muscle strength in each of the muscle groups tested and that the change scores were significant from the control group except for the left anterior deltoid. Study participants self-reported decreases in stress, pain, depression, enhanced physical self-concept and overall quality of life.

Drolet et al. (1999) conducted one of the first longitudinal studies published in muscle strength changes in individuals with SCI during rehabilitation. Significant improvement of muscle strength during rehabilitation for individuals with both paraplegia and tetraplegia was noted. Significant improvements were noted at the three-month post discharge evaluation period with the tetraplegia group in the four muscle groups (elbow flexors and extensors and shoulder flexors and extensors) and then began to plateau. One year later elbow flexors showed significant improvement in both paraplegia and tetraplegia groups and shoulder extension showed significant gains only on individuals with paraplegia. Large variability was noted indicating the recovery of strength may be influenced by a variety of individual factors such as level and severity of injury, associated health conditions, age, gender, motivation and physical condition before SCI. Improvements in strength realized in rehabilitation continue to be maintained or improved when the person with a SCI returned to community living.

Haisma et al. (2006) found positive changes in the different components of physical capacity both during and after inpatient rehabilitation. SCI subjects continued to improve and this study illustrates the importance of regularly assessing the physical capacity of people with SCI after discharge. It is important to create conditions (education, exercise facilities) that facilitate further improvements (Haisma et al. 2006).
Cameron et al. (1998) also reported improvements in upper limb strengths in combination with NMS.

Haisma et al. (2006) and Sipski and Richards (2006) recommended further research in this area:

- Further research is needed to document benefits of exercise interventions post-SCI including optimal methods for strengthening muscles, merits of endurance versus strength training, ROM, gait, ADL, and transfer training.
- Due to impact of body composition, age, concomitant medical problems and our limited knowledge of recovery post SCI, research needs to be performed through well-designed multicentre trials.
- Longitudinal studies are needed to gain more insight into the changes that occur after inpatient rehabilitation and the factors which influence these changes.
- Exercise and strengthening of the upper limb in both the acute and subacute phase of rehabilitation are important in promoting independence and prevention of injury.

Conclusions

There is level 2 evidence (from one randomized controlled trial; Hicks et al. 2003) that physical capacity continues to improve after 1-year post discharge.

There is level 1b evidence (from one randomized controlled trial; Needham-Shrophire et al. 1997) that neuromuscular stimulation-assisted exercise improves muscle strength over conventional therapy.

There is level 4 evidence (from one case series study; Cameron et al. 1998) that neuromuscular stimulation-assisted ergometry alone and in conjunction with voluntary arm crank exercise was an effective strengthening intervention for chronically injured individuals.

There is level 4 evidence (from one pre-post study; Drolet et al. 1999) that muscle strength continues to improve up to 15 months post hospital discharge for both tetraplegic and paraplegic individuals.

Neuromuscular stimulation-assisted exercise following a SCI is effective in improving muscle strength, preventing injury and increasing independence in all phases of rehabilitation.

3.0 Augmented Feedback on Motor Functions

Several studies have addressed the use of augmented feedback, such as biofeedback, with spinal cord injured populations. van Dijk et al. (2005) conducted a systematic review of RCTs on the effect of augmented feedback on motor function of the affected upper extremity in rehabilitation patients. Much of the information about augmented feedback comes from the motor learning literature where it has been noted that feedback combined with practice is a potent variable for affecting motor skill learning (Newell 1991; Schmidt & Lee 1999). There are two types of performance-related information or feedback. The first type of feedback, task intrinsic or inherent feedback, is sensory-perceptual information and is a natural part of performing a skill. The second type of feedback is augmented feedback or information-based extrinsic or artificial feedback. Augmented feedback refers to enhancing task intrinsic feedback.
with an external source (Magill 2001; Schmidt & Lee 1999), such as a therapist or device (biofeedback or timer) (van Dijik et al. 2005). It has been suggested that augmented feedback may have practical implications for rehabilitation therapy since re-acquisition of motor skills is an important part of functional motor recovery (Jarus 1994; Jarus & Ratzon 2005; Kilduski & Rice 2003; Weinstein 1991).

The ability to use intrinsic feedback to guide performance is impaired in patients with cognitive and perceptual impairments (Flinn & Radomski 2002). In persons who are compromised by neurological sensory impairments, augmented feedback is important (Sabari 2001).

A systematic review (van Dijik et al. 2005) found three randomized clinical controlled trials which studied augmented feedback in the SCI population (Klose et al. 1990; Klose et al. 1993; Kohlmeyer et al. 1996). In our literature search we were able to find an additional two other studies with lower level of evidence that studied augmented feedback applications.

Table 2 Augmented Feedback on Motor Functions

<table>
<thead>
<tr>
<th>Author Year</th>
<th>Country</th>
<th>Score</th>
<th>Research Design</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
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<tbody>
<tr>
<td>Kohlmeyer et al. 1996</td>
<td>USA</td>
<td>PEDro=10</td>
<td>RCT</td>
<td>N_{Initial}=60, N_{Final}=45</td>
<td>Population: Mean age=39 yr; Gender: males=40, females=5; Level of injury: C4-C6; Severity of injury: complete, incomplete injuries. Treatment: Extremities were randomly assigned to 1 of 4 treatment groups: 1. conventional strengthening; 2. electrical stimulation; 3. biofeedback and electrical stimulation; 4. biofeedback. Participation ranged from 5 to 6 weeks post SCI. Outcome Measures: manual muscle test- scoring and ADL performance.</td>
<td>1. Comparison of Groups (Increment or Decrement or No Change): no relationship between treatment group and observed change; no treatment produced a significantly higher proportion of individuals that improved relative to the proportion showing no change or a decrement; no change between treatment groups. 2. Influence of Initial Muscle Grade: a correlation between the initial muscle grade and increment in muscle grade was seen at the end of treatment; poorer initial muscle grades, more likely to see a larger increment in muscle grade as a result of treatment. 3. Conclusion-biofeedback and electrical stimulation both alone + together did not prove to be more effective than standard therapy for wrist extensor recovery during the acute phase of rehabilitation.</td>
</tr>
<tr>
<td>Popovic et al. 2006</td>
<td>Canada</td>
<td>PEDro=6</td>
<td>RCT</td>
<td>N=21</td>
<td>Population: Age=25-70 yr; Level of injury: tetraplegia; Severity of injury: AIS A-D, incomplete; Time Since Injury=15-243 days; Chronicity=acute/subacute. Treatment: The control group received conventional Occupational Therapy; Intervention group received Functional Electrical Therapy and conventional Occupational Therapy. Outcome Measures: Functional Independence Measure (FIM); Spinal Cord Independence Measure (SCIM); Rehabilitation Engineering Laboratory</td>
<td>1. A great deal of variance between participants in most measures due to low numbers of subjects, no significant differences was found between the Control and Intervention groups.</td>
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<tr>
<td>Author Year</td>
<td>Country</td>
<td>Score</td>
<td>Research Design</td>
<td>Total Sample Size</td>
<td>Methods</td>
<td>Outcome</td>
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<tr>
<td>Klose et al. 1993</td>
<td>USA</td>
<td>PEDro=5</td>
<td>RCT</td>
<td>NInitial=31; NFinal=28</td>
<td>Hand Function Test (REL Test); Consumer Perceptions.</td>
<td>1. Scores after training indicated no significant differences for the muscle test score and functional activities score between groups. 2. Analysis of the repeated measures factor showed a significant change for the manual muscle test and functional activities score (p&lt;0.05).</td>
</tr>
<tr>
<td>Klose et al. 1990</td>
<td>USA</td>
<td>PEDro=3</td>
<td>RCT</td>
<td>NInitial=43; NFinal=39</td>
<td>Population: Age=18-45 yr; Level of injury: C4-C6; Severity of injury: incomplete; Time since injury=at least 1yr post injury. Treatment: All received 3 days/wk of therapy in 2 consecutive eight week treatment blocks. Treatment blocks were as follows; Group 1: Biofeedback followed by supervised physical therapy exercise Group 2: Biofeedback followed by neuromuscular stimulation (NMS); Group 3: NMS followed by physical therapy exercise; Group 4: 16 weeks physical therapy exercise. Outcome Measures: Manual muscle test assessed the biceps, triceps, wrist flexors and wrist extensors. Self-care measures looking at feeding, hygiene and dressing. Mobility measure and a muscle electrical activity were also measured.</td>
<td>1. No statistically significant differences were noted between the groups. 2. Differences were noted for the repeated measures of mobility, self-care, and the left arm muscle test scores (p&lt;0.05). 3. The repeated measures factor was statistically significant in all of the analyses looking at measures of physical function (p&lt;0.01) but not in those that compared EMG values.</td>
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<td>Brucker &amp; Bulaeva 1996</td>
<td>USA</td>
<td>Pre-post</td>
<td></td>
<td>N=100</td>
<td>Population: Age=17-63 yr; Gender: males=81; females=19; Level of injury: C2-C6; Time since injury=1-29.7 yr. Treatment: EMG biofeedback treatment sessions. Outcome Measures: EMG scores.</td>
<td>1. T-test analysis of the differences before and after initial biofeedback treatment was done. An increase of 19.21% of normal EMG scores for right triceps and increase of 19.59% of normal EMG scores from the left triceps from one biofeedback treatment session were found, significant (p&lt;.001). 2. T-test analysis of the difference from before initial biofeedback treatments to after additional treatments, increase in percentage of normal EMG scores of 41.55% right triceps and 38.31% left triceps, significant (p&lt;.001). Increases in percentage of normal EMG scores after initial biofeedback treatment to after additional biofeedback treatment 22.3% right triceps and 18.72% for left triceps, significant (p&lt;.001).</td>
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<tr>
<td>Author</td>
<td>Year</td>
<td>Country</td>
<td>Score</td>
<td>Research Design</td>
<td>Total Sample Size</td>
<td>Methods</td>
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</table>

**Note:** ADL=Activities of Daily Living; AIS=ASIA Impairment Scale; EMG=Electromyography; Independence Measure.

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**Discussion**

All of the studies concluded that there was no evidence of the effectiveness of the use of augmented feedback to improve arm function in rehabilitation. In a systematic review, van Dijik et al. (2005) recommended the following be considered in future research in this area:

- future studies need to focus on content, form and timing of the augmented feedback to clarify its importance in rehabilitation
- studies should recognize the difference between performance and learning effects concerning reacquisition of motor skills by re-examining the study population after a follow up period

**Conclusion**

*There is level 1a evidence (from two randomized controlled trials; Kohlmeyer et al. 1996; Popovic et al. 2006) that augmented feedback is not effective in improving upper limb function in tetraplegia.*

Augmented feedback does not improve motor function of the upper extremity in SCI rehabilitation patients.

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**4.0 Pharmacological Interventions**

Cervical injuries of the spinal cord frequently lead to hypertonia characterized by disabling spasticity and dystonia involving the upper and lower limb. Spasticity has been defined by Lance (1980) as “a velocity exaggerated increase in the tonic stretch reflexes (muscle tone) resulting from hyperactivity of the stretch reflex.” The EU-SPASM Thematic Network or Consortium (Support Network for the Assembly of Database for Spasticity Measurement) has presented an updated definition of spasticity that reflects a recent research findings and current clinical interpretations. Spasticity has been re-defined as “disordered sensori-motor control, resulting from an upper motor neurone lesion, presenting as intermittent or sustained involuntary activation of muscles” (Pandyan et al. 2005).

The management of severe cases of hypertonia can be challenging as it can be refractory to oral medications. Many studies have shown that intrathecal delivery of balcofen has been
effective for refractory hypertonia in the lower extremity. Baclofen, 4-amino-3 (p-chlorophenyl) butyric acid works by binding to the inhibitory presynaptic GABA-B receptors in the spinal cord (Meythaler et al. 1999). Intrathecal delivery of the drug facilitates achievement of therapeutic levels in the cerebral spinal fluid (CSF) while minimizing systemic side effects (drowsiness, confusion). Burns and Meythaler (2001) is the only study published which deals with hypertonia involving the upper extremity post-SCI. Further discussion regarding the management of hypertonia can be found in the spasticity chapter.

Table 3 Pharmacological Interventions

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<thead>
<tr>
<th>Author Year Country</th>
<th>Score</th>
<th>Research Design</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
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<tr>
<td>Burns &amp; Meythaler 2001 USA</td>
<td>N=14</td>
<td>Case Series</td>
<td></td>
<td>Population: Age=25-64 yr; Level of injury: C4-C7; Severity of injury: AIS A-D; Time since injury=1.2-24 yr.</td>
<td>1. Significant decline in UE hypertonia during 12 month follow up period.</td>
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<td>Treatment: Intrathecal baclofen.</td>
<td>2. Average baseline Ashworth score was 2.4±1.1 (SD) compared to 1.8±1.0 (SD) at 12 months (p&lt;0.0001).</td>
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<td>Outcome Measures: Ashworth Scale; Spasm Frequency Scale; Reflex Scale.</td>
<td>3. The average spasm score decreased from 2.3±1.6 (SD) to 0.5±0.9 (SD), not significant at p=0.2503 (Friedman test).</td>
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<td>4. The difference was significant (p=0.0012 Wilcoxon signed rank test). UE reflexes, average baseline reflex score was 2.3±0.2 (SD) compared to 0.9±0.2 (SD) at 12 months (p&lt;0.0001 Friedman).</td>
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<td>5. Dosage requirements increased during the 12-month follow-up period, statistically significant (p&lt;0.0001, Friedman).</td>
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<td>6. Statistically significant declines in upper extremity spasm scores (1.8 points, p=0.012), reflex scores (1.4 points, p&lt;0.0001) and Ashworth scores (0.6 points, p&lt;0.0001) for the 1-year follow-up period.</td>
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</table>

Note: AIS=ASIA Impairment Scale

Discussion

Burns and Meythaler (2001) showed a statistically significant decrease in Ashworth (tone) and reflex scores in upper extremity hypertonia due to pathology at the level of the spinal cord.

Conclusion

*There is level 4 evidence (from one case series study; Burns & Meythaler 2001) that intrathecal baclofen may be an effective treatment for upper extremity hypertonia of spinal cord origin.*

Intrathecal baclofen may be an effective intervention for upper extremity hypertonia of spinal cord origin.
5.0 Restorative Strategies

5.1 Plasticity of Motor Systems

It has been reported that 55% of all spinal cord injured persons are classified as having complete injuries. Magnetic resonance imaging (MRI) and histopathology indicates that approximately 65% of the traumatic injuries initially classified as ‘neurologically complete’ (absence of sensory and motor function in lowest sacral segment) show some tissue and axonal sparing across the lesion (Bunge et al. 1997). It is now accepted that the CNS is capable of substantial reorganization, especially in incomplete SCI because cortical, subcortical and much of the local spinal cord circuitry remains largely intact and still partially interconnected by unlesioned fibres (Raineteau & Schwab 2001). Information may still pass through the level of the lesion on spared fiber tracts but the information may be fragmented or distorted (Beekhuizen & Field-Fote 2005). Functional recovery can occur for several years after injury in incomplete SCI, with the degree of recovery dependent upon the reorganization of circuits that have been spared by the lesion (Green et al. 1999). Cortical reorganization occurs after SCI with evidence that the sensorimotor cortex may play a role in the recovery of function in individuals with SCI (Green et al. 1999). Results of neuroimaging and neurophysiological techniques (functional magnetic resonance imaging (fMRI), transcranial magnetic stimulation (TMS) and positron emission tomography (PET) demonstrate that changes occur in the cortex following damage to the spinal cord with expansion of cortical areas corresponding to muscles spared after SCI into the cortical areas previously associated with control of muscle reinnervated at spinal cord levels below the level of the lesion (Bruehlmeier et al. 1998; Cohen et al. 1991; Levy et al. 1990; Raineteau & Schwab 2001).

In ISCI, reorganization might occur at two levels; in pre-existing circuits by modifications of synaptic strength (synaptic plasticity) or by new circuits through sprouting or anatomical reorganization, including growth of axonal branches and dendrites (anatomical plasticity) (Raineteau & Schwab 2001). Laboratory work is currently explaining and researching cortical reorganization, cortical plasticity, sub-cortical plasticity, plasticity at the red nucleus, plasticity and spontaneous adaptation of the central pattern generators and plasticity of unlesioned descending pathways. The strengthening and weakening of synapses, axonal and dendritic sprouting can occur at different levels of motor system in response to spinal cord lesions, in the cortex, the brainstem, and the spinal descending pathways and in the intraspinal circuits. All interact with each other; therefore it is difficult to interpret functional recovery processes. A SCI interrupts distinct descending fibre populations. The overall complexity of an incomplete SCI resides first in the organization of descending spinal tracts. Most of the descending systems terminate on spinal interneurons, but some direct excitatory or inhibitory connections to motor neurons also exist. Different tracts are involved in specific functions. For example, lesions of the cortical and rubrospinal systems lead to more severe and longer lasting deficits for movement of the distal extremities and lesions of the reticulo and vestibulospinal systems affect movements of proximal and axial muscles. Functional outcomes of given spinal cord lesions therefore depends on type of fibres that are interrupted (Raineteau & Schwab 2001).

Functional reorganization is based on two mechanisms; synaptic plasticity in pre-existing circuits and sprouting and anatomical reorganization that leads to the formation of new circuits. The study of animal models provides further understanding of rehabilitation treatments and development of new therapeutic approaches for people with SCI (Raineteau & Schwab 2001).

Traditional approaches to improving arm and hand function in persons with tetraplegia generally use compensatory strategies to have the muscles that are intact substitute for the lost function.
of the weakened or paralyzed muscles and management of musculoskeletal complications as described in the Guidelines for Clinical Practice for the Consortium for Spinal Cord Medicine Clinical Practice Guidelines supported by the PVA 2005 (Backus 2010).

Based on the neuroplasticity research, there is a belief that there are similarities between incomplete tetraplegia after SCI and hemiplegia after stroke as incomplete tetraplegia often have altered and inappropriate sensory input and motor output and not simply the loss of sensory or motor function (Backus 2010). Persons with hemiplegia who have altered (but not absent) sensory perception and paresis (but not complete paralysis) demonstrate disordered motor control in the ULs which include the ability to balance agonist and antagonist muscles (Chae et al. 2002; Levin et al. 2000), strength imbalances (Lum et al. 2002), disruptions in initiation and cessation of movement (Chae et al. 2002) and inappropriate muscle activation (Kamper et al. 2001). Persons with tetraplegia, much like hemiplegia experience the inability to effectively activate and deactivate (relax) muscles at appropriate time and extent. The difficulty is seen in being able to control the strength or force output during movement and the altered timing and control of movement at a joint or across multiple joints. Based on this, it is thought that ISCI is said to closely resemble hemiplegia (Backus 2010).

There are several principles underlying the facilitation of neural plasticity and functional recovery such as intense activity, repeated practice, attention and somatosensory augmentation concurrent with movement practice. The interventions usually combine intense, repetitive and often rhythmic input to CNS below the level of injury. These principles are the basis for constraint induced movement therapy approach and activity based intervention (ABInt) (i.e., treadmill training, FES approach, constraint-induced therapy). The goal of ABInt is to facilitate long term changes in spinal and cortical circuits and improve overall function after neural injury or disease. Until the past decade, studies researching the use and effectiveness of ABInt for improving function and potentially neural activity in arm and hand in persons with tetraplegia have been limited and scared in the upper limb literature (Backus 2010). The research studying the use of massed practice (MP) and/or somatosensory peripheral nerve stimulation (SS) have demonstrated potential for both neural and functional improvements in persons with tetraplegia (Beekhuizen & Field-Fote 2005; Beekhuizen & Field-Fote 2008; Hoffman & Field-Fote 2007).

Three studies were found that tested the use of MP, SS and repetitive transcranial magnetic stimulation (rTMS) in changing the cortex.

### Table 4 Restorative Strategies

<table>
<thead>
<tr>
<th>Author Year Country Score Research Design Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
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<tr>
<td>Beekhuizen &amp; Field-Fote 2005 USA PEDro=8 RCT N=10</td>
<td>Population: Age=22-63 yr; Gender: males=9, females=1; Level of injury: C5-C7; Severity of injury: AIS C=4, D=6; Time since injury=12-154 months. Treatment: Subjects participated in 2h of massed practice (MP) therapy 5/wk for 3 wk or MP+median nerve somatosensory stimulation (SS). MP training focused on continuous repetitions of the following: gross upper extremity movement, grip, and grip with rotation, pinch and pinch with rotation. Tasks in each block were performed for 25 min before moving to the</td>
<td>1. Pinch grip scores: differences were noted in the MP+SS group (Z=-2.023, p&lt;0.05) only. 2. The MP+SS group also showed greater increase in pinch grip strength than the MP group (U=2.0, p&lt;0.05). 3. Upper extremity Functional tests: the Pre/post Wolf Motor Function Test timed scores in the MP+SS group showed a difference (Z=-2.023, p&lt;0.05). No statistical differences were noted for the MP</td>
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<tr>
<td>Author Year Country Score Research Design Total Sample Size</td>
<td>Methods</td>
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<td>next category.</td>
<td>Outcome Measures: Maximal pinch grip force, Wolf motor function test timed task scores, Jebson hand function test scores, stimulus intensity required to elicit motor threshold response in muscles, and motor evoked potentials amplitude.</td>
<td>group.</td>
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<td>4. Timed test scores between the 2 groups were also found to be statistically different (U=1.0, p&lt;0.05).</td>
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<td>5. Jebson test scores: pre and posttest scores were different for the MP+SS group (Z=-2.023, p&lt;0.05). The MP+SS group showed greater improvement than the MP group (U=3.0, p&lt;0.05).</td>
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<td>6. Cortical Excitability: No significant differences were noted between the 2 groups.</td>
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<td>Beekhuizen &amp; Field-Fote 2008 USA PEDro=5 RCT NInitial=24; NFinal=18</td>
<td>Population: Mean age=38 yr; Gender: males=22, females=2; Level of injury: tetraplegia; Severity of injury: AIS C=11, D=13; Time since injury=67 months; Chronicity=chronic. Treatment: One of four conditions 2 hours per day, 5 days per week: 1) Massed practice training (MP); 2) Somatosensory peripheral nerve stimulation (SS); 3) MP +SS combined; 4) No intervention (control). Outcome Measures: Functional hand use: Jebson-Taylor Hand Function Test; Functional upper extremity use (Wolf Motor Function Test); Pinch and grip strength (Key pinch force); Sensory function (Monofilament testing); Cortical excitation change (Motor evoked potential thresholds).</td>
<td>1. Intervention groups differed significantly in hand function (p&lt;0.001). All intervention groups had a significant improvement in their hand function (MP, p&lt;0.01; SS, p&lt;0.05; MP+SS, p&lt;0.001), as compared to the control group. The MP+SS group improved more than the MP and SS group alone (p&lt;0.01).</td>
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<td>2. MP+SS and SS groups significantly improved motor function scores when compared to the control group (p&lt;0.01, p&lt;0.05, respectively). MP+SS improved more than MP and SS alone (p&lt;0.01).</td>
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<td>3. MP+SS and SS groups also significantly improved pinch grip forces (p&lt;0.01).</td>
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<td>4. MP+SS was the only group to have a significant sensory function improvement (p=0.01).</td>
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<td>Belci et al. 2004 UK Pre-post N=4</td>
<td>Population: Age=41-54 yr; Gender: males=3, females=1; Level of injury: C5; Severity of injury: AIS D; Time since injury=1.25-8 yr. Treatment: 5 days of sham repetitive transcranial magnetic stimulation (rTMS) followed by 5 days of therapeutic stimulation (rTMS). Outcome Measures: AIS and 9 Hole Peg Board.</td>
<td>1. No difference between patients when looking at the assessments done after baseline and after sham intervention.</td>
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<td>2. The level of intracortical inhibition was reduced to 37.5±8.0% of pretreatment levels during the week of therapeutic treatment (p&lt;0.05) and returned to 90.2±15% of pre-treatment levels during the follow-up period.</td>
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<td>3. This was linked to improvements in clinical measures of both motor and pinprick of 4-10% during treatment week. (p&lt;0.05).</td>
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<td>4. Subjects also improved perceptual threshold to electrical stimulation of the skin and peg board test scores (p&lt;0.05).</td>
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*Note: AIS=ASIA Impairment Scale; SS=Somatosensory Peripheral Nerve Stimulation*
Discussion

Beekhuisen and Field-Fote (2005) suggested that MP or constraint-induced therapy promotes cortical reorganization that may be an effective rehabilitative tool for improving strength and function in individuals with cervical SCI. Improvement may be further enhanced by the addition of somatosensory stimulation. Beekhuisen and Field-Fote (2008) showed that the use of MP with somatosensory peripheral nerve stimulation (SS) and the use of SS only showed significant improvements in upper extremity function and pinch strength when compared to the results demonstrated by the control group. The study also showed that use of MP and SS together had a significant change in sensory scores and the MP with SS and MP groups only showed greater change in threshold measures of cortical excitability when compared to the control group results. Belci et al. (2004) observed clinical changes consistent with the concept that reduced corticospinal inhibition can facilitate functional recovery. Recovery involved increased AIS sensory and motor scores, improved response to cutaneous electrical stimulation over the thenar muscles and possibly improved hand/finger function. This preliminary study demonstrated rTMS treatment in patients with chronic stable incomplete SCI can produce reductions in corticospinal inhibition detectable using electrophysiological techniques. Additional research studies with appropriate controls are needed to confirm the overall effectiveness of the intervention.

There is a lack of studies evaluating the efficacy of restorative strategies. In order for these therapies to be successful in everyday clinical practice, the therapy interventions need to be associated with meaningful changes in functional motor performance and incorporate techniques that are available in the clinic and at home (Beekhuizen & Field-Fote 2005).

Conclusion

There is level 1a evidence (from two randomized controlled trials; Bekkhuizen & Field-Fote 2005, 2008) that showed that massed practice (repetitive activity) and somatosensory stimulation (median nerve stimulation) demonstrated significant improvement in upper extremity function, grip and pinch strength required for functional activity use.

There is level 4 evidence (from one pre-post study; Belci et al. 2004) that showed that rTMS treatment in individuals with chronic stable ISCI may produce reductions in corticospinal inhibition that resulted in clinical and functional changes for several weeks after treatment.

Afferent inputs in the form of sensory stimulation associated with repetitive movement and peripheral nerve stimulation may induce beneficial cortical neuroplasticity required for improvement in upper extremity function.

Restorative therapy interventions need to be associated with meaningful change in functional motor performance and incorporate technology that is available in the clinic and at home.
5.2 Complementary Alternative Therapies

Acupuncture is an ancient Chinese therapy practiced for more than 2500 years to cure disease and relieve pain (Lee & Liao 1990). There are 361 identified acupoints that have been formed into a network of 14 channels called the meridians. Acupuncture therapy has been shown to be effective in improving functional outcomes in hemiplegic stroke patients and in paraplegic spinal cord injured patients (Cheng et al. 1998). In electrical acupuncture therapy, electrical stimulation is provided directly to the acupoint areas. It has been speculated that acupuncture therapy through the correct acupoints and meridians in the acute SCI episode will assist in the minimization of posttraumatic cord shrinkage and sparing of the ventral horn neurons (Politis & Korchinski 1990; Ran et al. 1992; Tsay 1974; Wu 1990).

Table 5 Complementary Alternative Therapies

<table>
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<tr>
<th>Author Year Country</th>
<th>Score Research Design</th>
<th>Total Sample Size</th>
<th>Population</th>
<th>Methods</th>
<th>Outcome</th>
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<tr>
<td>Wong et al. 2003 Taiwan PEDro=5 RCT N=100</td>
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<td>Mean age=35 yr; Gender: males=80, females=20; Level of injury: paraplegia=63, tetraplegia=37; Severity of injury: AIS A-B; Chronicity=acute.</td>
<td>Acupuncture was administered to the treatment group via 4 x 5 cm adhesive surface electrodes at the acupoints of bilateral Hou Has (S13) and Shen Mo (B62). Frequency was set at 75 hz with a pulse duration of 200 usec and the magnitude of stimulation was set at 10 mV. Sessions were 30 minutes, 5 times per week.</td>
<td>1. Acupuncture group - sensory, motor + FIM scores improved significantly day of D/C + 1yr after injury (p&lt;0.05). Control group - only motor score significant improvement at 1yr post injury F/U p=0.023. 2. Comparison of AIS + FIM scores of both groups not at admission; D/C + 1yr post significant improvement AIS + FIM in acupuncture vs. control p&lt;0.05. 3. More patients in acupuncture group improved to AIS grade B + C or better at D/C + 1yr post p&lt;0.05.</td>
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</table>

Note: AIS=ASIA Impairment Scale

Discussion

With acupuncture thin metal needles are inserted into specific body sites and slowly twisted manually or stimulated electrically. The uncomfortable pain sensation or de qi, a prerequisite for effective acupuncture therapy, is induced by needle manipulation (Wong et al. 2003).

The randomized control trial by Wong et al. (2003) studied the use of electrical acupuncture therapy through adhesive surface electrodes and concomitant auricular acupuncture therapy in improving the neurologic or functional recovery in acute traumatic SCI patients. The study demonstrated that in the acupuncture group all sensory, motor and FIM scores improved significantly when examined on the day of discharge from hospital and one year after injury (p<0.05). The control group (auricular acupuncture) demonstrated only significant improvement in motor score at one-year post injury follow up (p=0.023). At discharge and at one year post injury follow up, the acupuncture group revealed significant improvement in all AIS and FIM scores when compared to the control group (p<0.05). An inherent bias may have been introduced into this study as the reviewer who assessed the participants was not blinded to the group assignment.

Conclusion
There is level 2 evidence (from one randomized controlled trial; Wong et al. 2003) that showed that the use of concomitant auricular and electrical acupuncture therapy may improve the neurological and functional recovery of acute spinal cord injured individuals.

The use of concomitant auricular and electrical acupuncture therapies when implemented early in acute spinal cord injured persons may contribute to neurologic and functional recoveries in spinal cord injured individuals with AIS A and B.

5.3 Splinting

Splinting of the upper extremity in the management of tetraplegia is a well-accepted therapy intervention and has been an accepted practice for many years in the management of SCI especially in the acute phase of injury for the prevention of contractures and for joint protection (Curtin 1994; Krajnik & Bridle 1992). The therapeutic goals of splinting are the immobilization, protection and support of the joints of the wrist and hand, prevention of joint malalignment, prevention and reduction of soft tissue shortening and contractures, prevention of soft tissue overstretch, counteracting hypertrophic scars, support of weak muscles, improvement of function and pain relief (Curtin 1994; Krajnik & Bridle 1992; Paternostro-Sluga & Stieger 2004). It has been shown that elbow flexion contractures greater than 25 degrees have significant impact on the independence with the spinal cord injured person especially in the ability to transfer and complete depression lift for pressure relief (Bryden et al. 2004; Dalyan et al. 1998; Grover et al. 1996). The most common static hand splints for tetraplegic patients are the resting pan or paddle splints, wrist extension splints (Futuro-type splint, long opponens splint and dorsal cock-up splint and spiral splint), short hand splints and tenodesis splints (Curtin 1994). Splints are also used to position the elbow in extension as flexion contractures of this joint are very common due to lack of triceps innervation and the effects of increased tone and spasticity (Bryden et al. 2004; Grover et al. 1996).

Table 6 Splinting of the Hand

<table>
<thead>
<tr>
<th>Author Year</th>
<th>Country</th>
<th>Score</th>
<th>Level Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
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</table>
| Harvey et al. 2006 Australia PEDro=8 RCT N_initial=44; N_final=43 | Population: Injury type: SCI=23, Stroke=14, ABI=7; Time since injury=4 yr. Treatment: Experimental group: thumbs splinted into a stretched, abducted position, every night (average 8 hours), for 12 weeks. Control group: no intervention. With the bilateral thumb group, splinting was applied to one thumb and no splinting to the other (own control). With unilateral thumb, subjects were divided into experimental and control. Outcome Measure: Palmar abduction of carpometacarpal joint; Subjective attitudes of effectiveness and convenience of splinting. | 1. After 12 weeks, control thumbs carpometacarpal angle mean change was 45-47°. Experimental thumbs carpometacarpal angle mean change was 45-47°. The mean difference between these two groups was 1°. 2. 22 experimental subjects wanted to continue with the splinting regime and 20 experimental subjects said their thumb web space extensibility was increased by the splinting. 3. The intra-class correlation coefficient between carpometacarpal angle of the control and unaffected thumbs, before and
<table>
<thead>
<tr>
<th>Author Year Country Score Level Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>DiPasquale-Lehnerz 1994 USA PEDro=4 RCT NInitial=13; NFinal=9</td>
<td>Population: Age=18–42 yr; Gender: males=12, females=1; Time since injury=6–8 wk. Treatment: Experimental group was given long or short orthosis to be worn at night (8hrs) as soon as the subject could tolerate it. Outcome Measure: Pinch strength and functional activity use.</td>
<td>1. No significant differences were noted between the 2 groups—all subjects demonstrated improvement in hand function and pinch strength. 2. At 8 weeks the 13 subjects showed improvement in their performance on the checkers subtest (p&lt;0.01), simulated feeding subtest (p&lt;0.01), and the large light object subtest (p&lt;0.01). 3. At the 12-week marker, improvement could be seen on the card subtest (p&lt;0.05). 4. An increase in pinch strength was noted at 8 weeks for all subjects (p&lt;0.05) and at 12 weeks 9 remaining subjects (p&lt;0.05)</td>
</tr>
</tbody>
</table>

**Discussion**

Even though splinting and orthotic fabrication is an accepted practice, there is minimal research data on the effectiveness of this intervention (DiPasquale-Lehnerz 1994; Krajnik & Bridle 1992), although there are numerous anecdotal descriptions of orthotic devices and rationales for orthotic intervention (DiPasquale-Lehnerz 1994). Curtin (1994) and Krajnik and Bridle (1992) also found formal assessments were often not done due to; a lack of time and staff shortages; inconsistent documentation; absence of standardized tests available for spinal cord injured patients; limited funding to purchase equipment; and/or patient declined to participate in formal assessments due to boredom and frustration. Krajnik and Bridle (1992) noted that therapists considered observation of the patient when involved in a functional activity as the most informative assessment although this was not an objective means of documenting a patient’s status and progress. There appears to be a variety of splints made for similar purposes because there is little research as to what splint is best for the level and stage of SCI (Krajnik & Bridle 1992). It was noted by Harvey et al. (2006) that the use of splints are also viewed as a major inconvenience to both the client and therapist and the overall effect of the splint needs to be substantial in order to justify the inconvenience and discomfort. Harvey et al. (2006) also reported that clients were initially agreeable to wear splints at the beginning of their treatment, but by the end of treatment they were less compliant.

In Paternostro-Sluga and Steiger’s (2004) review, the therapeutic aims of splinting and the choice of splint depend on the disease and the individual functional problem resulting from the impairment. These authors also concluded that there is insufficient evidence from clinical trials on splinting strategies in CP or SCI patients. The studies also referred to research looking at hand splints for clients with an acquired brain injury or stroke (McPherson et al. 1982; Rose & Shah 1987).
Harvey et al. (2006) noted in their study that twelve weeks of nightly stretch does not reduce thumb web-space contractures in people with a neurological condition (stroke, ABI, SCI). Even with careful monitoring of the fit of the splint for the thumb joint, it was unclear if the splint was able to produce enough torque to the thumb joint for a sufficient stretch. The study also raised questions concerning if the length of time wearing the splint was enough, if the time spent wearing the splint was accurately reported by the client and if there a difference in outcomes when considering the type of neurological condition being splinted.

DiPasquale-Lehnerz (1994) noted that there was no significant improvement in hand function as it related to passive ROM, strength of prehension or coordination in subjects with C6 tetraplegia who wore a thumb opponens orthoses during sleep as compared to those subjects with C6 tetraplegia who did not wear such an orthosis. The study did show over time a significant improvement of hand function especially pinch strength, and functional use (turning cards, picking up small objects, simulated feeding and holding onto light cans) for those wearing the splint.

There are several published surveys that addressed the use of splints in the spinal cord population with the majority of splints being functional use splints (i.e., feeding splint, writing splint, typing splint or an application for an assistive device) (Garber & Gregoria 1990; Krajnik & Bridle 1992). More research is needed in this area using larger study sizes and studying the type of neurological condition being splinting prior to determining if splinting is effective in contracture reduction.

Conclusion

*There is level 2 evidence (from one randomized controlled trial; DiPasquale-Lehnerz 1994)* that wearing a thumb opponens splint will improve pinch strength and functional use of the hand.

*There is level 1b evidence (from one randomized controlled trial; Harvey et al. 2006)* that 12 weeks of nightly stretch with a thumb splint did not reduce thumb web-space contractures in persons with a neurological condition (i.e., stroke, ABI, SCI).

There is clinical and intuitive support for the use of splinting for the prevention of joint problems and promotion of function for the tetraplegic hand; however, there is very little research evidence to validate its overall effectiveness.

6.0 Subacute Phase of Rehabilitation

6.1 Upper Limb Injuries

A spinal cord injured individual is forced to rely on their upper extremities for their weight bearing activities such as transfers, mobility needs and ADLs using limbs that were designed to place hands in space (Consortium for Spinal Cord Medicine 2005; Dalyan et al. 1999; Dyson-Hudson & Kirshblum 2004). Repeated use of the upper limb for weight bearing activities such as manual wheelchair propulsion, transfers, raised ischial pressure reliefs (weight shifts) and reaching from a seated position in the wheelchair in environments designed for nondisabled individuals places a great deal of stress on the bones, joints and soft tissues of the shoulder complex. This places the structures of the upper limb at significant risk for overuse and subsequent injury (Dyson-Hudson & Kirshblum 2004). Pain in the early post injury period is
typically due to increased demands on anatomically weakened muscles or muscle weakness induced because of deconditioning.

Upper limb pain is known to interfere with a wide range of functional activities, transfers, ambulation, pressure relief and self-care (Curtis et al. 1995a, Dalyan et al. 1999); many individuals report alteration/cessation of activities critical to functional independence (Pentland & Twomey 1994; Sie et al. 1992). Shoulder pain may be functionally and economically equivalent to a higher level of lesion (Salisbury et al. 2003). Dalyan et al. (1999) reported that of individuals with upper limb pain, 26% needed additional help with functional activities and 28% reported limitations of independence. Subbarao et al. (1994) and Gerhart et al. (1993) reported that individuals with SCI reported that their dependence in personal care assistants fluctuated with upper limb pain and was a major reason for functional decline. The Consortium for Spinal Cord Medicine (2005) has written clinical practice guidelines “Preservation of Upper Limb Function Following Spinal Cord Injury: A Clinical Practice Guideline for Health Care Professionals,” as a way to address upper limb problems.

6.1.1 Shoulder Injuries

Upper limb pain and injury are highly prevalent in people with SCI and consequences are significant. The Consortium for Spinal Cord Medicine (2005) and Dyson-Hudson and Kirshblum (2004) reported through surveys and cross-sectional studies that shoulder pain in chronic spinal cord injured persons are common in both paraplegia and tetraplegia at a prevalence of 30-73%. In the acute phase after SCI, shoulder pain is reported in approximately 75% of patients (Silfverskiold & Waters 1991; Waring & Maynard 1991), and 33% to 63% of patients in the chronic phase (>6 months) experience shoulder pain (Nepomuceno et al. 1979; Sie et al. 1992; Silfverskiold & Waters 1991). Curtis et al. (1995a), Nichols et al. (1979) and Pentland and Twomey (1991) reported in cross sectional studies that 60-100% of long-term wheelchair users experience shoulder pain. Subbarao et al. (1994) and Sie et al. (1992) reported that there is a high prevalence of shoulder pain during the first year after injury, and in individuals 15-20 years post injury. Pain experienced above the injury level during the first 3-6 months after injury is different than the pain experienced 1 year or more after injury (Apple 2001). Pain above the level of injury in chronically injured person assumes the character of overuse syndromes (Apple 2001). Injury involving the shoulder, elbow, wrist and hand are seen at an earlier age in spinal cord injured individuals than in the general population because of the stresses of weight bearing and mobility that are added to the normal use of the upper limb (Pentland & Twomney 1994). Individuals who are older at the time of injury may experience functional changes earlier than people who are injured at a younger age (Thompson 1999).

It is also very difficult to determine whether shoulder pain is a function of duration of SCI or simply a part of the normal aging process (Neer & Welsh 1977). The wide variability in these numbers is most likely a reflection of the heterogeneity of participant populations between the studies with respect to duration of injury, age, neurologic level and severity of injury, as well as body mass index. Small sample size, selection bias and variations in participant populations across the different studies with respect to duration of injury, age, gender and neurological level and severity of injury make it difficult to assess the true prevalence of shoulder pain in individuals with shoulder pain (Pentland & Twomey 1991). The incidence of shoulder pain in acute tetraplegia (<6 months post injury) has been reported to range from 51% to 78% (Salisbury et al. 2003).

Nichols et al. (1979) was one of the first groups to report an association between chronic SCI and shoulder pain coining the term “wheelchair user’s shoulder. “ Due to the prevalence of
shoulder pain, Curtis et al. (1995b) developed a Wheelchair Users’ Shoulder Pain Index (WUSPI) that measures the severity of pain for 14 functional activities.

The following are the many identified risk factors for the development of injury and pain in the upper limb.

- The shoulder is the most common joint above the level of injury where pain complaints are reported with persons with paralysis (tetraplegia or paraplegia) (Apple 2001).
- The shoulder is not well designed to handle the higher intra-articular pressures required for both weight bearing and mobility (Apple 2001).
- Partial innervation and impaired balance of shoulder, scapular and thoracolumbar muscles place individuals with tetraplegia at a higher risk for developing shoulder pain especially during weight-bearing upper limb activities such as wheelchair propulsion, transfers, and pressure reliefs.
- Due to differences in trunk postural control, differences may also occur between individuals with high paraplegia (T2-T7) and low paraplegia (T8-T12).
- Individuals with C1-C4 motor levels of injury are also at risk for shoulder pain.
- SCI severity also may be associated with shoulder pain (Dyson-Hudson & Kirshblum 2004).
- Lack of use of immobilization of the shoulder girdle muscles can limit their active joint movement and lead to muscle shortening and shoulder capsule tightness.
- The development of pain is associated with decreased shoulder ROM.
- Weakness and paralysis in these muscles can lead to increased reliance on the trapezius, which can result in overuse and pain in this muscle.
- Shoulder pain can occur from nerve root injury or radicular pain with dysesthesias or phantom sensations.
- People of certain age groups, those with higher cervical lesions and those with shorter lengths of bed rest may be at a greater risk.
- Gender may be associated with shoulder pain in individuals with SCI (Pentland & Twomey 1991).
- Body mass index (BMI) also may play a role in shoulder injuries in manual wheelchair using individuals with SCI because it directly relates to the amount of physical strain experienced during ADLs in these individuals (Boninger et al. 2001; Jensen et al. 1996).
- Shoulder pain is more common in individuals with tetraplegia and complete injuries and in women and duration of injury, older age, and higher BMI all may be risk factors for developing shoulder pain and/or abnormalities in persons with SCI (Dyson-Hudson & Kirshblum 2004).

### 6.1.2 Elbow/Wrist and Hand Injuries

The prevalence of elbow pain and injury has been reported to be between 5-16% (Consortium for Spinal Cord Medicine 2005). Sie et al. (1992) found 15% and 16% rates of pain localized in the elbow region in persons with tetraplegia and paraplegia. Dalyan et al. (1999) in their study found 35% complained of elbow pain.

The prevalence of carpal tunnel syndrome is reported to be between 40-66% (Consortium for Spinal Cord Medicine 2005). There are four studies that found an association between length of time since injury and prevalence of carpal tunnel syndrome (Aljure et al. 1985; Gellman et al. 1988; Schroer et al. 1996; Sie et al. 1992). Some studies also found median nerve damage without clinical symptoms.

### Table 7 Shoulder Treatment Interventions

<table>
<thead>
<tr>
<th>Author</th>
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<th>Country</th>
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<th>Total Sample Size</th>
<th>Methods</th>
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<th>PEDro Score</th>
<th>Research Design</th>
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<tr>
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<td>PEDro=7</td>
<td>RCT</td>
<td>N=21</td>
</tr>
<tr>
<td>Hicks et al. 2003</td>
<td>Canada</td>
<td>PEDro=5</td>
<td>RCT</td>
<td>NInitial=32; NFinal=24</td>
</tr>
<tr>
<td>Curtis et al. 1999</td>
<td>USA</td>
<td>PEDro=5</td>
<td>RCT</td>
<td>N=42</td>
</tr>
</tbody>
</table>

### Methods

**Population:** Age=28-69 yr; Gender: males=18, females=6; Time since injury=5-33 yr; Length of shoulder pain=4 mo -22 yr.

**Treatment:** Subjects received either acupuncture treatments (sessions lasted 20 to 30 min) or Trager Psychophysical Integration - sessions lasted approx 45 min. Consisted of both table work and Mentastic™ exercises (easy, natural movement sequences to enhance relaxation and decrease pain during table work).

**Outcome Measures:** Intake questionnaire (demographics and medical history), Weekly log, Wheelchair users shoulder pain index (WUSPI), Numeric rating scale, Verbal rating scale (VRS), Range of Motion (ROM).

1. There was a significant effect of time for both treatments on performance corrected (PC)-WUSPI (Acupuncture p<0.001 and Trager p=0.001).
2. Overall a reduction of the PC-WUSPI could be seen when looking at the data from the beginning of treatment to the end for both groups (p<0.05)
3. There was a significant effect of time for both acupuncture and Trager groups for average pain & most severe pain (p<0.01, p<0.001 respectively), for the least severe pain the acupuncture group showed a significant reduction (p<0.01) compared to the Trager group.
4. Verbal response scores- there was a statistically significant treatment effect for both groups (p=0.001).

**Population:** Age=19-65 yr; Level of injury: C4-L1; Severity of injury: AIS A-D; Time since injury=1-24 yr.

**Treatment:**Experimental group participated in a progressive exercise training twice weekly for 9 months each session offered on alternative days lasting 90-120 minutes. Control group were offered educational sessions bimonthly (exercise physiology for SCI osteoporosis, post SCI relaxation methods).

**Outcome Measures:** Perceived stress scale, muscle strength, depression, physical self-concept pain, perceived health and Q of L were assessed.

1. EX group reported less pain, stress and depression after training + scored higher than CON in indices of satisfaction with physical function, level of perceived health + overall quality of life (p<0.05).
2. Following training, EX gr. had significant increases in sub maximal arm ergometry power output (81%; p<0.05) and significant increases in upper body muscle strength (19-34%; p<0.05).

**Population:** Mean age=35 yr; Gender: males=35, females=7; Level of injury: cervical to lumbar; Duration of wheelchair use=24 yr.

**Treatment:** Both groups completed the Wheelchair Users Shoulder Pain Index (WUSPI) every 2 mo for 6 mo. The experimental group attended a 60min educational session where they were instructed in 5 shoulder exercises.

**Outcome Measures:** Self report questionnaire (demographic and medical info), Wheelchair User's Shoulder Pain Index (WUSPI), and a visual analog scale (VAS) used to rate intensity of pain.

1. There were no significant differences between control and experimental group in age, years of wheelchair use or activity levels.
2. When looking at the effect of exercise of intervention on performance corrected (PC) WUSPI, a 2 factor repeated measures ANOVA showed a significant effect of time only (p=0.048).

**Note:** AIS=ASIA Impairment Scale; Q of L=Quality of Life; VAS=Visual Analog Scale;

### Discussion

The most significant activities causing pain in the wrist and hand are reported to be propelling a
wheelchair and doing transfers (Subbarao et al. 1994). Management of established upper limb pain is very difficult and thus prevention is critical. Evidence-based best practice standards have not been established for the medical, rehabilitative or surgical treatment of upper limb injuries in people with SCI. In addition, there is little consensus among health-care providers on the best treatment practices for upper limb injuries in the general population. In general, musculoskeletal upper limb injuries in the SCI population are managed in a similar fashion as the unimpaired population.

Outcome studies of surgical treatment in SCI also very limited. Two small studies report the outcome of rotator cuff repair – one showing relatively poor results (Goldstein et al. 1997) and another study showing relatively good outcomes (Robinson et al. 1993). Both studies recommend non-surgical approaches prior to surgical intervention. One randomized controlled trial found that supervised exercise produced results similar to arthroscopic surgery for patients with impingement syndrome (Brox et al. 1993), however; this study was not on SCI patients.

Exercise has been shown to reduce pain in a randomized controlled trial in which subtypes of pain were not reported (Hicks et al. 2003). Two studies found an association between restricted ROM and pain, reduced activity and/or injury (Ballinger et al. 2000; Waring & Maynard 1991). A study incorporating stretching into an exercise program for individuals who use manual wheelchairs found stretching exercises were associated with decreased reported pain intensity (Curtis et al. 1999).

One study demonstrated that acupuncture was no more effective than Trager Treatment in the treatment of shoulder pain (Dyson-Hudson et al. 2001). There are several studies that address the use of complementary or alternative medicine (CAM) with the spinal cord population, which is used at similar rates to the general population. It was reported that the most common reason CAM was used, was for dissatisfaction with conventional medicine for treatment of chronic pain (Nayak et al. 2001). The only CAM technique evaluated in the SCI population is acupuncture although studies do not provide conclusive evidence of effectiveness (Dyson-Hudson et al. 2001; Nayak et al. 2001; Rapson et al. 2003).

Psychological interventions among non-SCI individuals with chronic pain are popular and it has been suggested that selected approaches may be useful for those with SCI (Consortium for Spinal Cord Medicine 2005). Cognitive-behavioural strategies have been found to produce changes in pain experience, increase positive cognitive coping and appraisal skills and reduce pain behaviours (Morley et al. 1999). There are mixed results for the use of relaxation training for relief of chronic pain (Carroll & Seers 1998), which may also have secondary beneficial effects on muscle tension and emotional distress (Astin et al. 2002; Leubbert et al. 2001). Cognitive-behavioral interventions have not been subjected to controlled trials as to their effectiveness in the SCI population (Wegener & Haythornthwaite 2001).

As identified in the Consortium for Spinal Cord Medicine (2005) document, modification of task performance based on ergonomic analysis has been proven to reduce the incidence of upper limb pain and cumulative trauma disorders of the upper limb in various work settings (Carson 1994; Chatterjee 1992; Hoyt 1984; McKenzie et al. 1985). It is suggested that these same interventions can be used to prevent pain and injury in SCI. Although the number of studies linking activities of individual with SCI to injury may be small, the ergonomics literature provides a strong basis for evidence-based practice. Recently, Rice et al. (2013) studied the impact of a strict education protocol in the implementation of the clinical practice guideline “Preservation of Upper Limb Function Following Spinal Cord Injury” addressing the impact of an education protocol on transfer skills and wheelchair propulsion. The study demonstrated a positive effect
on the importance of proper education in improving the quality of transfers and better wheelchair propulsion biomechanics as key elements in reducing the risk of shoulder injury and pain (Rice et al. 2013).

The Consortium for Spinal Cord Medicine (2005) Clinical Practice Guideline Preservation of Upper Limb Function published the following recommendations regarding the upper limb:

- Both the spinal cord injured person and the clinician need to be educated about the prevalence of upper limb pain and injury and the potential impact of pain and possible means of prevention
- Routinely assess the patient’s function, ergonomics, equipment and level of pain as part of periodic health review
- Assessment of risk factors, changes in medical status, new medical problems, changes in weight
- Reduce the number of non-level transfers per day
- Assess work related activities
- Re-evaluate current exercise program (strengthening, stretching, conditioning)

Dyson-Hudson et al. (2001) in a randomized controlled trial compared acupuncture treatment to Trager Psychosocial Integration performed by a certified Trager practitioner. The authors noted that trager therapy is a form of bodywork and movement re-education to induce relaxation and encourage the patient to identify and correct painful patterns. The theory is that chronically contracted muscles induced by stress led to pain (Dyson-Hudson et al. 2001). There was a significant effect over time for both treatment groups in reducing shoulder pain, but there was no difference between the two groups.

Curtis et al. (1999) in a randomized controlled trial and Hicks et al. (2003) studied the effectiveness of a six-month exercise and stretching protocol on shoulder pain experienced by wheelchair users. The data supported the effectiveness of this exercise and stretching protocol in decreasing the intensity of shoulder pain that was interfering with functional activity of wheelchair users.

The Consortium for Spinal Cord Medicine (2005), Sipski and Richards (2006), Campbell and Koris (1996), Dalyan et al. (1999), and Nichols et al. (1979), have identified the following as important areas of further research in the upper limb:
Conclusions

There is level 1b evidence (from two randomized controlled trials; Hicks et al. 2003; Curtis et al. 1999) that a shoulder exercise and stretching protocol reduces the intensity of shoulder pain post SCI.

There is level 1b evidence (from one randomized controlled trial; Dyson-Hudson et al. 2001) that general acupuncture is no more effective than Trager therapy in reducing post-SCI upper limb pain.

Shoulder exercise and stretching protocol reduces post SCI shoulder pain intensity.

Acupuncture and Trager therapy may reduce post-SCI upper limb pain.

Prevention of upper limb injury and subsequent pain is critical.

7.0 Reconstructive Surgery and Tendon Transfer

7.1 Hand

The loss of upper limb function especially the use of the hand is one of the most significant and devastating losses an individual can experience. Tetraplegia is responsible for many problems in daily living, mostly related to the recovery and/or preservation of independence for the tetraplegic individual (Welraeds et al. 2003). The study by Hanson and Franklin (1976) showed recovery of hand function was preferred to that of the bladder, bowel or even sexual function
among tetraplegics. In a survey of tetraplegic patients, 75% responded that hand function was very important for their independence in ADL and to increase their quality of life (Snoek et al. 2004). In another study conducted in the United States with a sample of individuals with tetraplegia, 42% of the individuals viewed upper limb function as their top restoration priority (the function they wanted restored first) and 44% of the surveyed individuals reported an interest in receiving upper extremity reconstructive surgery (Wagner et al. 2007).

Reconstructive surgery is one option to attempt to improve the function of the hand and upper limb in persons with tetraplegia. Functionally, the benefit of reconstructive surgery may be evident as improved ability to write, complete catheterizations, dress, self-feed, drive, lift objects, button, turn dials, propel their wheelchair, catch objects overhead, turn in bed and swim are only some of the activities that become possible after surgery (Rabishong et al. 1993). Surgery has been reported to improve quality of life for those people who had little or no upper limb function (Freehafer et al. 1984).

Despite the many reported studies, over 40 documented studies, hand reconstructive surgery is not common practice in many spinal units and its importance in improving hand function still remains controversial (Forner-Cordero et al. 2003). Guttmann (1976), McSweeney (1969) and Bedbrook (1969) believed that only a small percentage of tetraplegics (5%) benefit from hand surgery because they re-adjust the function of their arm and hands if properly rehabilitated, while other authors like Moberg (1975) state that 75% of tetraplegics can obtain benefit from hand surgery. A recent review of epidemiologic data from the 1988 to 2000 in the USA found that only 7% of appropriate surgical candidates actually received surgery (Curtin et al. 2005). In a study completed by Wuolle et al. (2003), they surveyed individuals with tetraplegia who received upper extremity surgery, 70% of the individuals were satisfied with their results and 68% reported improvement in ADLs. These statistics are consistent with another study that surveyed physicians who estimated that there was 75% client satisfaction, suggesting that both the client and caregiver (physician and/or surgeon) view reconstructive surgery to be beneficial and satisfying (Wagner et al. 2007). Studies by Curtin et al. (2005) and Squitieri and Chung (2008) explored the reason for underutilization of reconstructive surgery in the tetraplegic population. Issues identified were; lack of clarity in the literature about the value of reconstructive procedures, lack of access to centres that perform reconstructive surgeries, lack of qualified and experienced hand surgeons and physiatrists who have an interest in this area of surgery and negative physician bias toward reconstructive surgery. Curtin et al. (2005) identified that it is important that there is good relationships between spinal cord specialists and surgeons (surgeons were 13.1 times more likely to perform surgery; physiatrists were 2.8 times more likely to refer clients for surgery).

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 (Freehafer et al. 1984). 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. 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. The sensibility was evaluated by the two-point discrimination test in the thumb and the index. If it is lower than 10mm the classification belongs to the group Cutaneous (Cu-) and if it is higher than 10mm and the patient needs visual help it is classified in the group Ocular (O-).
Table 8 Modified International Classification for Surgery of the Hand in Tetraplegia (McDowell et al. 1986)

<table>
<thead>
<tr>
<th></th>
<th>Sensory</th>
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<tbody>
<tr>
<td></td>
<td>O-</td>
</tr>
<tr>
<td>0</td>
<td>Weak or absent Brachioradialis (BR) ≤ grade 3</td>
</tr>
<tr>
<td>1</td>
<td>BR (≥ grade 4)</td>
</tr>
<tr>
<td>2*</td>
<td>BR, ECRL</td>
</tr>
<tr>
<td>3*</td>
<td>BR, ECRL, ECRB</td>
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<td>9*</td>
<td>Lacks intrinsics only</td>
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<tr>
<td><strong>Total</strong></td>
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</table>

Note: O- = Two-point discrimination in the thumb > 10mm; Cu- = Two-point discrimination in the thumb < 10mm; ECRL= Extensor Carpi Radialis Longus; ECRB= Extensor Carpi Radialis Brevis; PT= Pronator Teres; FCR= Flexor Carpi Radialis; *The listing of a muscle means that it is functional (grade 4 or better).

Candidates for reconstructive surgery are carefully selected and are followed by a rehabilitation team that includes an orthopedic surgeon, rehabilitation physiatrist, and therapist over a significant period of time. The identified criteria for selection are as follows: at least one year post-injury, completed a comprehensive rehabilitation program, neurologically stable, and psychologically adjusted to their injury.

The measure of outcomes following reconstructive surgery continues to be debated in the literature. Many of the reported studies on surgical outcomes are older, are case series evaluations and lack the rigor of randomized controlled trials, and have subjective outcomes based on reported client satisfaction. In addition, there is little consensus in the literature on the assessment instruments and tools to be used in this population as their reliability, validity and responsiveness have not been adequately proven. The methodology appears to be a major failing of the various scales and the absence of clear conceptual models forming the basis of their scales. Also, the scales or instruments have been deemed to be too insensitive to document the small but meaningful functional gains made by those with tetraplegia after functional surgery (Fattal 2004). Many authors state that comparing the post-surgical condition is the best way to evaluate results (Freehafer et al. 1984). There have been several articles published that discuss the use of the ICF conceptual framework as a way to interpret hand function outcomes following tendon transfer surgery for tetraplegia (Bryden et al. 2005; Sinnott et al. 2004).

The reconstructions of upper limb to obtain functions of pinch and grasp often require multiple procedure and are also individualized to each person. The reconstructions performed are also dependent on what motor muscles/tendons are present and strong enough for transfer (Kozin 2002). Dunn et al. (2012) completed a study that addressed client’s decision making process for reconstructive UL surgery and it was found that that a client's decision to have surgery were underpinned by 6 core influences. These influences were the overall outcome of surgery, the client's current goals and priorities in their life, the hope that their overall quality of life (QOL) would be improved, a stable home environment, available social supports and assistance for assisting with increased care needs post-surgery and access to information on surgery. It was also found that these factors were individualized to each person and is dependent on any number of issues at one time and can change in its priority over time. The most commonly performed surgeries for reconstructive pinch are:
Key-Pinch Grip – Brachioradialis to Extensor Carpi Radialis Longus, Flexor Pollicis Longus split 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 – Brachioradialis to Flexor Pollicis Longus with or without Flexor Digitorum Profundus tenodesis or Brachioradialis to Extensor Carpi Radialis Longus.

Key-Pinch Grip and Hook Grip – Brachioradialis or Pronator Teres to Flexor Pollicis Longus and Brachioradialis or Extensor Carpi Radialis Longus to Flexor Digitorum Profundus.

Additional procedures to increase thumb pinch and thumb opposition may also be completed.

**Table 9 Reconstructive Surgery – Pinch Studies**

<table>
<thead>
<tr>
<th>Author Year</th>
<th>Country</th>
<th>Score</th>
<th>Research Design</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>McCarthy et al. 1997</td>
<td>USA</td>
<td></td>
<td>Pre-post</td>
<td>N=135</td>
<td>Population: Age=8-58 yr; Gender: males=103, females=30; Level of injury: tetraplegia; Follow-up time=3-24 months. Treatment: Extrinsic hand reconstruction with intrinsic balancing procedures vs. extrinsic reconstructions without intrinsic balancing procedures. Outcome Measures: Pre and post-operative assessments of grip strength (on the second position of the Jamar dynamometer) and a patient questionnaire evaluating 31 ADLs.</td>
<td>1. All patients had preoperative grip strength of 0. At an average follow-up period of 31 months, the average final grip strength was 69N (7kg) and the ADL improvement score averaged 35.5. 2. Patients who underwent an intrinsic procedure had a statistically stronger grip (72N) than patients who did not undergo an intrinsic procedure (p=0.026). 3. Ocular group: 5 patients with an intrinsic procedure had a statistically stronger grip than patients without an intrinsic procedure (p=0.028). 4. With the exception of Ocular group 7, in which 8 patients did not undergo an intrinsic procedure due to their ability to balance tension between the extensors and flexors, all other Ocular groups with an intrinsic reconstruction showed stronger grip than patients without an intrinsic reconstruction. 5. ADL improvements scores were higher but not statistically significant for those with intrinsic rebalancing versus those without rebalancing. 6. There was significant difference between the hands treated by FDS lasso and those treated by intrinsic tenodesis when patients were stratified by Ocular level. 7. There was also no significant difference in grip strength results between the FDS lasso versus the intrinsic tenodesis procedures when stratified by both Ocular level and type of extrinsic reconstruction, both surgical techniques were effective in</td>
</tr>
<tr>
<td>Author Year</td>
<td>Country</td>
<td>Score</td>
<td>Research Design</td>
<td>Total Sample Size</td>
<td>Methods</td>
<td>Outcome</td>
</tr>
<tr>
<td>-------------</td>
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</tr>
<tr>
<td>House et al. 1992 USA Case Series</td>
<td>N=18</td>
<td><strong>Population:</strong> Age=16-29 yr; Gender: males=14, females=4; Level of injury: C5-C6; Time since injury=16 months to 12/13 yr. <strong>Treatment:</strong> Carpal-metacarpal fusion was performed; along with extensor pollicis longus tenodesis and motor transfer to flexor pollicis longus. <strong>Outcome measures:</strong> Function of the hand, subjective pain scale, &amp; level of satisfaction with surgery and rehabilitation.</td>
<td></td>
<td>Improving strength and ADL.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waters et al. 1985 USA Case Series</td>
<td>N=15</td>
<td><strong>Population:</strong> Age=20-47 yr; Gender: males=13, females=2; Time since injury=8 months - 18 yr; Follow-up time=8-48 months. <strong>Treatment:</strong> Surgery <strong>Outcome Measures:</strong> Pinch strength; ADL reports.</td>
<td></td>
<td>1. (Follow-up 1-10yr (average 3.5yr) 2. All patients reported a significant increase in independent hand function in relation to ADLs, no patient reported hand function was worse after surgery. 3. Technique provided a reliable and reproducible key pinch. 4. All patients had significant improvement in functional ADLs and highly satisfied with results of surgery.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
11. 20% (3/15) reported discomfort tip of thumb.

Table 10 Summary of Pinch Studies

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>N</th>
<th>Intervention</th>
<th>Main Outcome(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>McCarthy et al.</td>
<td>1997</td>
<td>135 patients (183 procedures)</td>
<td>Extrinsic reconstruction with Intrinsic Balancing vs. without Intrinsic Balancing FDS Lasso vs. Intrinsic Tenodesis for Intrinsic Balancing</td>
<td>+ve grip strength with intrinsic balancing =ADL and functional use =grip strength =ADL and functional use</td>
</tr>
<tr>
<td>House et al.</td>
<td>1992</td>
<td>18 patients (21 procedures)</td>
<td>CMC fusion EPL tenodesis BR 0r ECRL or ECRl to FPL As indicated: stabilization of thumb IP joint and Zancolli Lasso procedure</td>
<td>+ve pinch strength +ve ADL and functional use</td>
</tr>
<tr>
<td>Waters et al.</td>
<td>1985</td>
<td>15 patients (17 procedures)</td>
<td>BR to FPL (lateral pinch) with thumb IP joint stabilization (16 hands) 11 patients also had EPL tenodesis and EPB to metacarpal joint; 2/17 patients EIP to EPL procedure</td>
<td>+ve lateral pinch strength in all test positions +ve ADL functions +ve direct correlation between pinch strength and amount of residual triceps and wrist extensor strength</td>
</tr>
</tbody>
</table>

Note: ADL=Activities of Daily Living; BR=Brachioradialis; ECLR=Extensor Carpi Radialis Longus; FCR=Flexor Carpi Radialis; FDP=Flexor Digitorum Profundus; FPL=Flexor Pollicis Longus

+ positive outcome, =no difference, - negative outcome

Pinch and Grasp (Key-Pinch and Hook Grip)
The most commonly performed surgeries to obtain key-pinch and hook grip are:

Wrist Extension – If the person does not have adequate wrist extension, Brachioradialis (BR) to Extensor Carpi Radialis Brevis (ECRB) is performed prior to any surgery for pinch reconstruction.

Key-Pinch and Hook Grip – 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 (Lamb & Chan 1983).

Table 11 Reconstructive Surgery: Pinch and Grip Studies

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Country</th>
<th>Score</th>
<th>Research Design</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meiners et al.</td>
<td>2002</td>
<td>Germany</td>
<td></td>
<td></td>
<td></td>
<td>Population: Age=21-57 yr; Gender: males=21, females=3; Time since</td>
<td>1. Operative interventions on the tetraplegic hand brings gains in</td>
</tr>
</tbody>
</table>

Note: ADL=Activities of Daily Living; BR=Brachioradialis; ECLR=Extensor Carpi Radialis Longus; FCR=Flexor Carpi Radialis; FDP=Flexor Digitorum Profundus; FPL=Flexor Pollicis Longus

+ positive outcome, =no difference, - negative outcome
<table>
<thead>
<tr>
<th>Author Year Country</th>
<th>Research Design</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kelly et al. 1985</td>
<td>USA Case Series N=24</td>
<td>Population: Age=19-60 yr; Gender: males=17; females=7; Level of injury: 11 in group III (normal shoulder control, elbow flexion, radial wrist extensors), 11 in group IV (same as group III with functioning FCR, PT &amp; triceps, weak fingers), 7 in group V (intrinsic hand muscle paralysis) 4 in group VI (did not classify in groupings, but had incomplete paralysis); Time since injury=1-17 yr; Follow-up time=1-17 yr. Intervention: Surgery. Outcome Measures: Not specified.</td>
<td>1. 7 extremities had had post deltoid to triceps transfer before opponensplasty; 24 patients, 11 (46%) had bilateral opponensplasty. 2. 35 opponensplasties were done. 22 flexor tendon transfers were done for voluntary grasp and then opponensplasty. 3. 14 patients (22 extremities) evaluated. 4. Subjects reported that they would have the operation again (95% of the extremities) and had improved function (91%). 5. One patient reported that function was unchanged; 1 was dissatisfied. Overall value of key pinch 35 extremities was 1.47 +/- 1.29 kg (mean +/- SD). 6. Grasp measured in 20 extremities; 2.81 +/- 2.89 kg (mean +/- SD) (range trace to 10kg). 7. Palmar pinch; 9 of 20 extremities (45%) achieved palmar pinch (1.04 +/- 1.02 kg; mean +/- SD) (range 0.20-3.0 kg). Palmar pinch achieved in 17% of the extremities in group III, 71% in group IV, and 33% in group V.</td>
<td></td>
</tr>
<tr>
<td>Rieser &amp; Waters 1986</td>
<td>USA Case Series N=23</td>
<td>Population: Age=mean=23.6yr; age at time of surgery: mean=29.8yr, time from injury to operation 6.2 yr; follow-up time of this study: 7.4 yr Intervention: Surgery. Outcome Measures: Not specified</td>
<td>1. Self-assessment questionnaire results indicated: power decreased since surgery in all patients.</td>
<td></td>
</tr>
<tr>
<td>Lo et al. 1998</td>
<td>Canada Case Series N=9</td>
<td>Population: Level of injury: C5-6; Time since injury=at least 1 yr. Intervention: Surgery. Outcome Measures: not specified.</td>
<td>1. All reported they would have surgery again. 2. Key pinch strength in non-op limbs was 1.0±1.3 kg, in surgically treated arms it was 1.2±1.1 kg. 3. Minnesota rate of manipulation: non-operative limbs were 1.50±0.25 sec, post-operative limbs was 2 min 56 secs±1 min 56 sec.</td>
<td></td>
</tr>
<tr>
<td>Colyer &amp; Kappelman 1981</td>
<td>USA Case Series N=8</td>
<td>Population: Age=16-36 yr; Time since injury=4months-18 yr. Intervention: Surgery. Outcome measures: Not specified.</td>
<td>1. 6 of 8 subjects were evaluated. Subjects indicated they were pleased with the surgery. 2. Hand function tests indicated an improvement (16-49% improvement). 5 of 6 subjects showed key grip strength remained constant.</td>
<td></td>
</tr>
<tr>
<td>Author</td>
<td>Year</td>
<td>Country</td>
<td>Score</td>
<td>Research Design</td>
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<tr>
<td>--------------</td>
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</tr>
<tr>
<td>Failla et al. 1990</td>
<td>USA</td>
<td>Case Series</td>
<td>N=8</td>
<td>Case Series</td>
</tr>
<tr>
<td>Forner-Cordero et al. 2003</td>
<td>Spain</td>
<td>Retrospective Follow-up</td>
<td>NInitial=15; NFinal=14</td>
<td>Retrospective Follow-up</td>
</tr>
<tr>
<td>Gansel et al. 1990</td>
<td>USA</td>
<td>Case Series</td>
<td>N=19</td>
<td>Case Series</td>
</tr>
</tbody>
</table>

**Note:** ADL=Activities of Daily Living; FCR=Flexor Carpi Radialis;

Table 12 Summary Pinch and Grip Studies

<table>
<thead>
<tr>
<th>Author</th>
<th>N</th>
<th>Intervention</th>
<th>Main Outcome(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forner-Cordero et al. 2003</td>
<td>15 patients (20 limbs)</td>
<td>PD to Triceps&lt;br&gt;BR to ECRB&lt;br&gt;Tenodesis of FPL&lt;br&gt;APL to CMC joint or arthrodesis of CMC joint&lt;br&gt;BR or ECRL or PT to EDC and EPL or tenodesis of extensor tendons&lt;br&gt;BR or ECRL or ECRB to FPL&lt;br&gt;PT or ECRL or BR to FDP</td>
<td>+ve key-pinch strength&lt;br&gt;+ve grip strength&lt;br&gt;=ADL and functional use&lt;br&gt;+ve patient satisfaction&lt;br&gt;-ve patient expectation</td>
</tr>
<tr>
<td>Meiners et al. 2002</td>
<td>22 patients (23 hands)</td>
<td>FCR to FDP&lt;br&gt;ECRL to FDP</td>
<td>+ve lateral and cylindrical grip&lt;br&gt;+ve satisfaction with surgery&lt;br&gt;+ve ADL and functional use</td>
</tr>
<tr>
<td>Lo et al. 1998</td>
<td>8 patients (12 procedures)</td>
<td>ERCL to FDP and BR to FPL</td>
<td>+ve satisfaction with surgery&lt;br&gt;+ve key-pinch and grip strength&lt;br&gt;+ve ADL functional use</td>
</tr>
<tr>
<td>Failla et al. 1990</td>
<td>8 patients (9 hands)</td>
<td>BR to FDP or FPL&lt;br&gt;BR or ECRL to FPL</td>
<td>+ve key-pinch and grip strength&lt;br&gt;+ve ADL functional use</td>
</tr>
<tr>
<td>Gansel et al. 1990</td>
<td>11 patients</td>
<td>11/11 PT to FDP&lt;br&gt;10/11 BR to FPL&lt;br&gt;1/11 BR to FDS</td>
<td>+ve finger flexion&lt;br&gt;+ve key-pinch strength&lt;br&gt;+ve ADL functional use</td>
</tr>
<tr>
<td>Rieser &amp; Waters</td>
<td>9 patients</td>
<td>Tenodesis of FPL, thumb IP joint</td>
<td>-ve result, bowstringing of</td>
</tr>
</tbody>
</table>
### 7.2 Elbow Extension

#### 7.2.1 Posterior Deltoid to Triceps

The most commonly performed surgery for elbow extension is using the posterior third of the deltoid (PD) to motor the triceps. This converts the transferred portion of the deltoid into a two joint muscle but causes no functional loss at the shoulder (Moberg 1975).

<table>
<thead>
<tr>
<th>Author Year</th>
<th>Country</th>
<th>Score</th>
<th>Research Design</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rabischong et al. 1993</td>
<td>France</td>
<td></td>
<td>Prospective Controlled Trial</td>
<td>N=20</td>
<td>Population: Mean age=33.6 yr; Level of injury: C6; Time since injury=28-173 months; Follow-up time=46.1 mo. 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.</td>
<td>1. The muscle was tested at 6 different lengths (130, 110, 90, 70, 45 and 0 degrees of elbow flexion) with the shoulder abducted at 90. 2. When compared, the absolute values (dimension of torque) were significantly different between groups (0.00001&lt;p&lt;0.002. 3. The expression of this relation (% of maximum values) revealed significant statistical differences (p&lt;0.002) at 90 and 70 degree of elbow flexion; peak torque was at 130 degrees in experimental group and 110 degrees in control group with a plateau between 110 and 70 degrees. 4. Length-tension relationship was fairly similar among control group, but great differences in experimental group.</td>
</tr>
<tr>
<td>Remy-Neris et al. 2003</td>
<td>France</td>
<td></td>
<td>Pre-post</td>
<td>N=16</td>
<td>Population: Mean age=27 yr; Gender: males=11, females=5; Severity of injury: AIS=16-20. Treatment: Surgery. Control group members sat on a chair, while the</td>
<td>1. Straight Arm Raising-statistically significant decrease in maximal shoulder abduction (mean 57 SEM 12 before, 14 SEM 6 after surgery). 2. Shoulder flexion increased after</td>
</tr>
</tbody>
</table>
Dukerley et al. 2000
UK
Case-Control
N_initial=15; N_final=11

**Population:** Age=23-38 yr; Time since injury=5-16 yr.
**Treatment:** Surgery.
**Outcome Measures:** Questionnaire, FIM, 10 m push, and the figure of 8 push.

1. Both groups scored identically on the FIM.
2. No significant differences in mobility were noted (p=0.256, and p=0.432).
3. Questionnaire was answered only by the treatment group; clients gave positive response to the questions.

Lacey et al. 1986
USA
Case Series
N=10

**Population:** Level of injury: C6-C7; Time since injury=24 months.
**Treatment:** Surgery.
**Outcome Measures:** Not specified.

1. No statistically significant differences between pre and post-operative 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
USA
Case Series
N_initial=22; N_final=18

**Population:** Time since injury=10-242 months.
**Treatment:** Surgery.
**Outcome Measures:** ADLs, and use of wheelchair.

1. 15 of 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 wheelchair, writing improved, and driving in a small percentage was positively affected.

Table 14 Summary Elbow Extension (Posterior Deltoid to Triceps)

<table>
<thead>
<tr>
<th>Author</th>
<th>N</th>
<th>Intervention</th>
<th>Main Outcome(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remy-Neris et al. 2003</td>
<td>5 pt 17 limbs</td>
<td>PD to triceps</td>
<td>+ve straight arm raise +ve speed of movement</td>
</tr>
<tr>
<td>Dunkerley 2000</td>
<td>5 elbows, 6 controls</td>
<td>PD to triceps</td>
<td>=surgical/control gr: FIM (adapted) 13 items =surgical/control gr: W/C propulsion 8m&amp;10 m push +ve elbow function indicated on questionnaire</td>
</tr>
<tr>
<td>Rabischong et al. 1993</td>
<td>Gr 1 - 8 pt 11 elbows Gr 2-control 9 R hand (female)</td>
<td>PD to triceps</td>
<td>Initial tension pt transfer at time of surgery is important for torque output + ve ADL and functional use</td>
</tr>
<tr>
<td>Lacey et al. 1986</td>
<td>10 pt 16 procedures</td>
<td>PD to triceps</td>
<td>+ve satisfaction with surgery +ve ADL and functional use</td>
</tr>
</tbody>
</table>
7.2.2 Biceps to Triceps

A biceps to triceps transfer can 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 (Kuz et al. 1999).

### Table 15 Reconstructive Surgery – Elbow Extension Studies (Biceps to Triceps Transfer)

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Country</th>
<th>Score</th>
<th>Research Design</th>
<th>NInitial</th>
<th>NFinal</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raczka et al. 1984</td>
<td></td>
<td>USA</td>
<td></td>
<td></td>
<td>18 pt</td>
<td>19 transfers</td>
<td>PD to triceps</td>
<td>+ve elbow extension strength +ve ADL and functional use</td>
</tr>
<tr>
<td>Kozin et al. 2010</td>
<td></td>
<td>USA</td>
<td>Case Series</td>
<td></td>
<td>N=45</td>
<td>40</td>
<td>Population: Mean age: 17.3 yr (range=66.4-21.7); Level of injury: 10 at C5, 29 at C6, 1 at C7. Treatment: Surgery for a biceps to triceps tendon transfer (36 left, 32 right). Outcome Measures: Manual muscle testing and Canadian Occupational Performance Measure.</td>
<td>1. Manual muscle testing for elbow extension revealed a statistically significant increase in preoperative to postoperative muscle strength (p&lt;.001). 2. 42/68 arms able to extend completely against gravity (manual muscle testing 3/5 or greater). 3. 9/68 arms had mild extension lag against gravity (manual muscle testing of 3/5). 4. 75% (51/68) arms were able to function overhead. 5. 17/68 arms were less than 3/5 (lack of strength attributed to a postoperative complication). 6. Improvement in one goal on the Canadian Occupational Performance Measure was observed by each patient. 7. Canadian Occupational Performance Measure total mean score statistically increased from 2.6 to 5.6 and from 1.8 to 5.7 for performance (p&lt;.001) and satisfaction (p&lt;.001), respectively.</td>
</tr>
<tr>
<td>Mulcahey et al. 2003</td>
<td></td>
<td>USA</td>
<td>RCT</td>
<td></td>
<td>N=9</td>
<td></td>
<td>Population: Gender: males=7, females=2; Level of injury: tetraplegic. ICSHT: 0-4; Tendon transfer for elbow extension: deltoids n=8, biceps n=8. Treatment: Surgery. Outcome Measures: Muscle strength, Flexion torque, Modified University of Minnesota Tendon Transfer Functional Improvement Questionnaire, Canadian Occupational Performance Measure (COPM).</td>
<td>1. After surgery, elbow extension muscle strength was improved in bicep and deltoid groups (p&lt;0.001). 2. No significant increase in elbow extension muscle strength was found following surgery. 3. 7 of 8 bicep-to-triceps procedures had clinical improvements in antigravity muscle strength, in comparison with 1 of 8 deltoid transfers completed. 4. No significant difference between the groups was found for elbow flexion torque (47% reduction in torque after 2 years versus baseline). 5. Following surgery, 48/63 elbow extension ADL did not improve in</td>
</tr>
</tbody>
</table>
subjects and there was no alteration in the remaining 15/63.  
6. Performance and satisfaction with personal goals improved post-surgery as well.

Kuz et al. 1999  
USA  
Case Series  
N=3  

**Population:** Level of injury: tetraplegia.  
**Treatment:** Surgery.  
**Outcome Measures:** Not specified.

1. No statistical results reported:  
2. Subjects indicated they were satisfied with the surgery.  
3. Activities that required precision hand placement had improved.  
4. Elimination of the need for some adaptive aids was possible post-surgery.

---

### Table 16 Summary Reconstructive Surgery - Elbow Extension Studies (Biceps to Triceps Transfer)

<table>
<thead>
<tr>
<th>Author</th>
<th>N</th>
<th>Intervention</th>
<th>Main Outcome</th>
</tr>
</thead>
</table>
| Kozin et al. 2010 | 40 patients 36 left; 32 right elbow surgeries | Biceps to Triceps                 | +ve elbow extension strength  
+ve reaching overhead  
Improvement in one goal on Canadian Occupational Performance Measure (COPM) for each patient  
Statistically significant improvement in performance and satisfaction scores on COPM |
| Mulcahey et al. 2003 | 9 patients 16 elbows | Biceps to Triceps  
Posterior Deltoid to Triceps | +ve elbow extension from either surgery  
+ve improvement in ADL skill (both surgeries)  
+ve antigravity strength (biceps to triceps > posterior deltoid to triceps) |
| Kuz et al. 1999   | 3 patients 4 elbows | Biceps to Triceps                 | +ve elbow extension  
+ve functional improvements through ability to place the hand in space  
+ve satisfaction with surgery |

+ positive outcome; - negative outcome

### 7.3 Multiple Reconstructions

The following studies report results from multiple procedures to reconstruct the upper limb.

### Table 17 Reconstructive Surgery – Multiple Reconstructions

<table>
<thead>
<tr>
<th>Author</th>
<th>Country</th>
<th>Score</th>
<th>Research Design</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
</table>
| Friden et al. 2012a | Sweden  | Pre-post | N=15            |                   | **Population:** Age range: 19-70 yr; Type of SCI: traumatic=12, non-traumatic=3; Level of injury: tetraplegia=15, paraplegia=0; Mean time since SCI: 54.2±42.8 mo; International classification of patients’ upper extremities: OCu4-OCu8 (with one patient who was exceptional).  
**Treatment:** All patients had their extensor | 1. Active thumb-index opening increased significantly from 2.5 (SEM 1.0) cm before surgery to 9.0 (SEM 0.8) cm after surgery.  
2. Nine patients without previous active opening of the first web space recovered a mean thumb-index opening of 9.1 (SEM 1.7) cm; this distance increased an average of 2.9 |
<table>
<thead>
<tr>
<th>Author Year</th>
<th>Country</th>
<th>Score</th>
<th>Research Design</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
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<tr>
<td>author year</td>
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<td>research design</td>
<td>total sample size</td>
<td>methods</td>
<td>outcome</td>
</tr>
<tr>
<td>author year</td>
<td>author year</td>
<td>author year</td>
<td>research design</td>
<td>total sample size</td>
<td>methods</td>
<td>outcome</td>
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</table>

**Methods**

- **digiti minimi (EDM) tendon transferred to the abductor pollicis brevis (APB) through the interosseous membrane, in addition to ≥3.2 procedures to restore key pinch.**

**Outcome Measures:** Maximum distance between the thumb and index finger tips during active or passive opening of the hand, maximum angle of palmar abduction, grip and key pinch strength, and active finger range of motion (ROM).

---

**Population:** Treatment group (n=6): Mean age: 32.2±4.9 yr (25-56); Gender: males=4, females=2; Control group (n=6): Mean age: 31.2±5.0 yr (19-52); Gender: males=4, females=2.

**Treatment:** Individuals in the treatment group had a brachioradialis (BR) to Flexor pollicis longus (FPL) transfer dorsal to radius through the interosseous membrane whereas the control group received traditional palmar BR to FPL.

**Outcome Measures:** Lateral key pinch and pronation range of motion (ROM).

1. Post-operative active pronation was significantly greater in the dorsal transfer group in comparison to the palmar group (149±6° and 75±3°, respectively).
2. Pinch strength was similar between both groups (1.28±0.16 kg and 1.20±0.21 kg), respectively.
3. It is feasible to reconstruct lateral key pinch and forearm pronation simultaneously using only the BR muscle.

---

**Population:** Mean age=42.9 yr; Time since injury=20.5 yr; Time since surgery=15.1 yr; Handedness: right=22, left=24; Level of Injury: 01: 6 hands; 02: 3 hands; 03: 5 hands; 0Cu2: 2 hands; 0Cu3: 6 hands; 0Cu4: 17 hands; 0Cu5: 8 hands; 0Cu6: 1 hand; 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 (key and grip pinch)

1. Elbow Extension: bilateral surgery 9/11 subjects; Hook Grip: 17 right hands (av. Grip 46.2 mm Hg in 1991; improved slightly, not statistical significant (p=0.30)) Left hand: 15 hands: significant increase (p=<0.001), av. 28.7 mmHg to 53.2 mmHg; no statistical significance between right and left hook grip as measured by SGM and DA in 2001 (p=0.93 and p=0.97).
2. Key Pinch: av. key pinch 20 right thumbs in 1991 25.8 N and decreased in time to av. 13.9 N (significant decrease p=<0.001); average pinch strength 18 left thumbs decreased from 17.7 to 8.8 N (significant decrease p=<0.001). Average pinch strength measured by DA, increase in key pinch when compared to 1991, significant for both right (p=0.01) and left (p=0.01) thumbs.
3. Active Transfer Vs. Tenodeses: hook grip: active transfers 2x strength of tenodeses in 1991 (p=0.05) and 2001 (p=0.03). Pinch grip: similar to 1991 data (p=<0.001), 2001 data does not follow trend. 2001 DA data did not reach significance (p=0.06).
4. Longitudinal Comparison: hook grip strength 25 hands with active transfers significant increase 42.1 to
<table>
<thead>
<tr>
<th>Author Year</th>
<th>Country</th>
<th>Score</th>
<th>Research Design</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Author Year</td>
<td></td>
<td>Model</td>
<td>60.2 mm Hg (p=&lt;0.001) and pinch grip increase from 24.0 to 38.4 N in 31 thumbs that had active transfers using 2001 DA data (p=0.03). Hook strength obtained from a tenodesis in 7 hands did not weaken over time (p=0.05) but pinch strength in 7 thumbs significantly increased (p=&lt;0.001) using 2001 DA data.</td>
</tr>
<tr>
<td></td>
<td>Mohammed et al. 1992</td>
<td>New Zealand</td>
<td>Case Series</td>
<td>N=57</td>
<td>Population:</td>
<td>Mean age=27 yr; Gender: males=51, females=6; Level of Injury: 00:4; 01: 6; 02: 4; 03: 6; 0X: 3; Cu3: 6; Cu 4: 24; Cu 5: 10; Cu 6: 3; Cu X: 3; 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.</td>
</tr>
</tbody>
</table>

1. No statistical analysis provided-gestural ability improved in more than 80% of the patients and functional gain was important in more than half.  
2. 43 procedures; Atypical procedures (2) good: 2; Moberg procedures (18) good: 17; poor: 1; Deltoid/triceps (12) good: 7; fair 3; poor 2; Additional procedures (11) good: 7; fair: 3; poor: 1. 

5. Questionnaire results; Lamb and Chan activity measure: showed perceived improvement of functional activities significantly lower in 2001 (p=<0.001). QIF scores of current functional independence was significantly better (p=0.004). Additional Burwood questionnaire showed levels of satisfaction, perceived expectation, gratification and opportunity enhancement were maintained over time (p=0.281).
<table>
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<tr>
<th>Author Year</th>
<th>Country</th>
<th>Score</th>
<th>Research Design</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ejeskar &amp; Dahllof 1988 Sweden</td>
<td>Case Series</td>
<td>N=43</td>
<td>Case Series</td>
<td>Case Series N=43</td>
<td>Population: Age=26-70 yr; Gender: males=36, females=7; Level of Injury: 0:1 9 pts; 0:2 2 pts; 0Cu:1 4 pts; 0Cu:2 13 pts; 0Cu:3 9 pts; 0Cu:4 5 pts; 0Cu:6 1 pt. Re-examined 1-14 yr after the last operation. 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).</td>
<td>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 (av. 0.7 kg); 15 cases had minimum of 1.0 kg. 3. Finger Flexion: 14 hand/13 patients (ECRL to profundi II-V); grip 0-0.27 kP (av. 0.13 kP); 5/14 minimum strength 1.0 kg. 4. 4 patients reported no improvement (1 severe spasticity, 2 BR muscle transferred to wrist; 1 operation on weaker hand); 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.</td>
</tr>
<tr>
<td>Freehafer et al. 1984 USA</td>
<td>Case Series</td>
<td>N=68</td>
<td>Case Series</td>
<td>Case Series N=68</td>
<td>Population: Mean age=15-61 yr; Level of injury: tetraplegia; Time since injury=1-17 yr. Treatment: Surgical reconstruction. Outcome Measures: Comparison of the post-surgical with the pre surgical condition.</td>
<td>1. One hundred forty two transfers were performed on 68 subjects. 2. No upper limbs were made worse. 3. Four remained unimproved, all others that had tendon transfers improved.</td>
</tr>
<tr>
<td>Lamb &amp; Chan 1983 UK</td>
<td>Case Series</td>
<td>N=41</td>
<td>Case Series</td>
<td>Case Series N=41</td>
<td>Population: Mean age=29 yr; Gender: males=38, females=3; Level of injury: tetraplegia; Severity of injury: complete; Follow up time=6 months - 25 yr. Treatment: Surgery. Outcome Measures: Elbow strength; Hand function (assessment checklist developed); ADL (developed checklist).</td>
<td>1. Elbow Function: 10/16 elbows (10 patients): full extension; 2/16 elbows 20 degree flexion contracture; 4/16 15 degrees of extension lag. All 10 patients considered the procedure beneficial. 2. Hand Function: 48 hands (assessed only 27 patients). 5 rated as excellent; 28 rated good; 11 rated as fair; 4 graded as poor. No patient had any impairment of hand function after operation. 3. ADL: 29 patients assessed. No one considered their functional capability deteriorated after operation. Most significant improvement in basic activities such as washing, eating and using the toilet, hold glasses and cups, wash limbs and brush hair, turn on taps, improve bladder compression, insertion of suppositories, change from complete reliance on other for self-care, more mobile, 7 able to drive a car. Improvement in UL function facilitated development of personal</td>
</tr>
</tbody>
</table>
### Table 18 Summary Multiple Reconstructions

<table>
<thead>
<tr>
<th>Author</th>
<th>N</th>
<th>Intervention</th>
<th>Main Outcome(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friden et al. 2012a</td>
<td>15 patients</td>
<td>EDM to APB</td>
<td>+ve key-pinch and grip strength</td>
</tr>
<tr>
<td>Friden et al. 2012b</td>
<td>12 patients</td>
<td>BR to FPL</td>
<td>+ve pinch strength</td>
</tr>
<tr>
<td>Rothwell et al. 2003</td>
<td>24 patients</td>
<td>BR to FPL or BR and tenodesis FPL</td>
<td>+ve key-pinch and hook grip</td>
</tr>
<tr>
<td></td>
<td>(48 reconstructions)</td>
<td>ECRL to FDP</td>
<td>+ve ADL and functional use</td>
</tr>
<tr>
<td>Welraads et al. 2003</td>
<td>25 patients</td>
<td>PD to Triceps</td>
<td>+ve elbow extension</td>
</tr>
<tr>
<td></td>
<td>(43 procedures)</td>
<td>ECRL to FDS</td>
<td>+ve key grip and grasp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BR to FDS</td>
<td>+ve ADL and functional use</td>
</tr>
<tr>
<td>Mohammed et al. 1992</td>
<td>57 patients</td>
<td>PD to Triceps</td>
<td>+ hook grip strength</td>
</tr>
<tr>
<td></td>
<td>(97 transfers)</td>
<td>Key-Pinch: BR or PT to ECRL; FPL tenodesis and IP stabilization Hook Grip: BR or ECRL to FDP</td>
<td>+ve ADL and functional use</td>
</tr>
<tr>
<td>Ejeskar &amp; Dahllof 1988</td>
<td>43 patients</td>
<td>PD to Triceps</td>
<td>-ve elbow extension</td>
</tr>
<tr>
<td></td>
<td>(94 transfers)</td>
<td>Tenodesis FPL, thumb IP joint stabilization ECRL to Profundus iv</td>
<td>+ve key-grip and finger flexion</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+ve ADL and functional use</td>
</tr>
<tr>
<td>Freehafer et al. 1984</td>
<td>68 patients</td>
<td>Variation of all procedures</td>
<td>+ve key-pinch and grip strength</td>
</tr>
<tr>
<td></td>
<td>(142 transfers)</td>
<td></td>
<td>+ve elbow extension</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+ve ADL and functional use</td>
</tr>
<tr>
<td>Lamb &amp; Chan 1983</td>
<td>41 patients</td>
<td>PD to Triceps</td>
<td>+ve elbow extension and function</td>
</tr>
<tr>
<td></td>
<td>(57 reconstructions)</td>
<td>Biceps to Triceps Hand Grip: ECRL to FDP BR to FPL Key-Pinch: FPL tenodesis or FPL tenodesis plus ECRL to FDP</td>
<td>+ve elbow extension (biceps to triceps)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Other: EPB to ECU, FCR to FDS, APB to EDM</td>
</tr>
</tbody>
</table>

Note: ADL=Activities of Daily Living; BR=Brachioradialis; ECLR=Extensor Carpi Radialis Longus
### Discussion

In reviewing the identified studies as a whole, the operative interventions on the tetraplegic hand and upper limb bring definite gains in pinch force, cylindrical grasp, and the ability to reach above shoulder height that result in an improvement in ADL function and quality of life for the individual with tetraplegia. Despite the low level of evidence (grade 4) the subjective acceptance among patients who have had reconstructive surgery is high. One of the reported downsides of surgery is the high complication rate (infection, torn attachments) and the extended period of time post-surgery for rehabilitation and increased need for personal care (Meiners et al. 2002).

Many SCI centres do not offer or have access to reconstructive surgery or neuroprosthesis interventions. It is also debated whether the overall cost of surgery or use of neuroprostheses is more beneficial to the client, as the client has to relearn new movement strategies in order to perform ADL (van Tuijl et al. 2002).

### Conclusion

*There is level 4 evidence (see Table 9-18) that support the use of reconstructive surgery for the tetraplegic upper limb for the improvement of ADL and quality of life.*

Reconstructive surgery appears to improve pinch, grip and elbow extension functions that improve both ADL performance and quality of life in tetraplegia.

### 8.0 Nerve Transfers

Recently, the literature is publishing information regarding the surgical procedure of nerve transfers which is evolving as an alternative procedure compared to tendon transfers for improving the functional ability of the hand and upper limb post SCI (Keith & Peljovich 2012). A nerve transfer involves the repair of distal denervated nerve element by using a proximal foreign nerve as the donor of neurons and their axons to re-innervate the distal targets (Addas & Midha 2009; Brown et al. 2012; Midha 2004). The transfer involves sacrificing the function of a lesser valued donor nerve to revive function in the recipient nerve and muscles, which is considered functionally more critical than the donor nerve (Senjaya & Midha 2013).

Senjaya and Midha (2013) and Midha (2004) described and listed the fundamental principles, advantages and potential drawbacks of nerve transfers when compared to tendon transfers in a review article and they are summarized in the following:

### 8.1 Fundamental Principles
1. The recipient nerve should be repaired as close as possible to the target muscle to ensure the shortest amount of time for re-innervation in an attempt to minimize distal denervation and motor end plate changes.

2. Donor nerve should be from a muscle whose function is expendable or has redundant innervation.

3. Nerve repair should be performed directly without intervening grafts.

4. Use of a donor muscle with pure motor fibers maximizes muscle fiber re-innervation.

5. Donor nerve should have a large number of motor axons and be a reasonable size match to the recipient nerve.

6. To facilitate motor re-education, a donor nerve that has a function synergistic to the muscle reconstructed should be used because cortical re-adaptation is the physiological basis of functional recovery.

7. Motor re-education improves functional recovery post operatively.

### 8.2 Advantages over Tendon Transfers

Nerve transfers have many advantages over tendon transfers.

1. Tendon transfers require significantly more dissection and extended post-operative limb immobilization while the tendon heals (Brown 2012). Less surgical scarring in common areas of the hand where tendons overlap anatomically, thus fewer chances of restricted motion (Keith & Peljovich 2012).

2. Reconstruction of finger flexion and extension must be done in separate phases, owing to conflicting positions for postoperative immobilizations (Revol et al. 2002) which maybe problematic for some who are highly dependent on others for care to be incapable of performing most basic ADL for quite some time (Bertelli et al. 2011; Brown 2012; Hentz 2002).

3. Tenotomy may cause detrimental effects on muscle function owing to the fact that reduced specific force is developed (Guelinekx et al. 1998).

4. Nerve transfers take a shorter period of less restrictive immobilization probably with less pain, minimal loss of donor muscle function (Brown 2012).

5. Reconstruction of finger flexion and extension can be done at the same time- tension-insertion balance of the muscle tendon unit is preserved because there is no disruption to the insertion or attachment of the muscle in question-maintaining line of pull and excursion and avoiding scar induced restrictions of movement (Brown 2012).

6. Nerve transfers offer a greater functional gain for a given transfer (Brown 2011; Brown 2012; Brown et al. 2012), the transferred axon, which originally provided re-innervation to a single muscle can re-innervate multiple motor fibers, later on with motor re-education and central plasticity, it is possible to activate multiple functions independently by the same nerve that initially controls only a single function (Brown 2011; Brown 2012; Midha 2004).

7. Nerve transfers can be accomplished without appreciable loss of function from the donor muscle group because nerve transfer can be performed with only a portion of the donor nerve, not entirely denervating the muscle associated with the donor nerve (Brown 2011; Brown 2012).

Although the partial denervation results in a reduced number of axons to the original muscle, the residual motor axons sprout within the muscle and innervate orphaned muscle fibers to enlarge the motor unit. Each motor axon can increase innervation 5x the number of muscle fibers that it originally served (Gordon et al. 1993). This phenomenon is called adoption (Brunelli & Brunelli 1983) and in time, the donor muscle may regain its original strength.
8.3 Potential Drawbacks of Nerve Transfers

There are also a few potential drawbacks of nerve transfers (Senjaya & Midha 2013).

1. When the donor nerve and its pertinent muscle sacrificed are of suboptimal function to begin with (MRC 3 or 4), nerve transfer may significantly downgrade its function.
2. An entirely denervated muscle, as a result of its nerve being donated is no longer suitable for muscle transfer donor.
3. Central motor re-education is needed to achieve functional recovery—this re-education can be challenging for patients, especially for nerve transfers from non-synergistic nerve.

8.4 Assessment and Surgical Timing

Prior to considering surgery, a detailed and careful assessment must be completed. Coulet et al. (2002) recommended assessing the following;

The extent of LMN injury at the injured metamere must be assessed and each key muscle group evaluated to determine;

a) type of motor neuron injury (LMN, UMN) by evaluating tone, trophic status, deep tendon reflex
b) joint ROM and deformities
c) electrodiagnostic studies are beneficial to determine extent of SCI

After a careful and complete evaluation, Coulet et al. (2002) recommended mapping the muscles to identify three the following:

a) Functional muscles (innervated by supraspenal segments)
b) Paralyzed and denervated muscles (innervated by injured metamere with damage to LMN)
c) Paralyzed but innervated muscles (innervated by infralesional segment, with preserved LMN)

The next assessment to be made is to decide what primary function to be restored. Kozin (2002) recommended the following priority: 1) restoration of elbow extension; 2) pinch restoration for hand function; and 3) grasp and release function.

Nerve transfers should be performed after a re-innervation window, to allow adequate waiting time to ensure optimal spontaneous recovery has been achieved for lesional level myotomes. Bertelli et al. (2011) recommended waiting at least 6 months. Re-innervation of muscle innervated by infralesional segment is not time-dependent and can performed years after injury (Bertelli et al. 2011).

8.5 Evidence

Restoration of elbow extension function is an integral part of UE reconstruction because recovery of this improves elbow stability, the ability to perform pressure relief maneuvers, push a manual wheelchair, reach for items and objects above shoulder height and the ability to complete functional transfers such as bed, toilet, tub and car transfers. To date there have been one case report (Brown et al. 2011) and one cadaver study (Bertelli et al. 2011) on nerve transfer for elbow extension function.
The primary goal of reconstruction in hands of a person with tetraplegia is the restoration of the ability to create a pinch using the thumb and lateral side of the index finger, for example when holding a key (Bertelli et al. 2012). To date there has been four published case reports (Bertelli et al. 2012; Mackinnon et al. 2012; Brown 2011; Hsiao et al. 2009) on nerve transfer for pinch and grip.

Finger extension is required for object acquisition (grasp) and object release (let go) (Kozin 2002). Two date there have been three case reports (Brown 2011; Bertelli et al. 2010; Palazzi et al. 2006) and one cadaver study (Bertelli et al. 2009) on nerve transfer for thumb and finger extension.

Conclusion

There are only a few reported and published studies on nerve transfer surgery for restoring hand and upper limb function after a SCI and based on the published literature, nerve transfer surgery is emerging as another surgical alternative.

| Nerve transfer surgery to restore hand and upper limb function in the person with tetraplegia is emerging as another surgical alternative. |

9.0 Neuroprostheses

A neuroprostheses for grasping is a device designed to improve or restore the grasping, holding and reaching functions in individuals with stroke and SCI (Baker et al. 1993; Cornwall & Hausman 2004). The neuroprostheses applies FES of the motor branches of the peripheral nerve in which paralyzed muscles are electrically stimulated to produce muscle contraction, replacing the electrical signals coming from the brain through the injured spinal cord (Shimada et al. 1996; Handa 1997; Hincapie et al. 2008). The FES uses bursts of short electrical pulses (pulse widths 0-250 mSec and pulse amplitude 0-150 mA) to generate muscle contraction by stimulating motoneurons or reflex pathways. The key element for achieving synergistic activity of muscles that results with reaching and grasping is the appropriate sequencing of bursts of electrical pulses. For continuous contraction of the arm and hand muscles (tetranization), a FES system has to deliver at least 16 stimulation pulses per second to elicit action potentials (AP) in the motor nerve, causing the corresponding muscles to contract. FES enables the patients with high SCI to reconstruct grasp movements such as palmar and lateral grasps of the upper extremity (Shimada et al. 2003). The palmar grasp is used to hold bigger and heavier objects such as cans and bottles and the lateral grasp is used to hold smaller and thinner objects such as keys, paper and CDs (Popovic et al. 2002). It has been reported to be useful in improving ADL functions (Popovic et al. 2001a; Shimada et al. 1996). FES is also applied to generate elbow extension by stimulating the triceps brachii in combination with voluntary biceps contraction used to augment reaching (Grill & Peckham 1998; Popovic et al. 1998). Elbow and shoulder FES systems have not been developed into practical clinical devices.

The motor nerves can be stimulated using surface (transcutaneous), percutaneous or implanted electrodes (Mortimer 1981). Transcutaneous stimulation is performed with self-adhesive or non-adhesive electrodes that are placed on the subject’s skin in the vicinity of the motor point of the muscle that needs to be stimulated (Baker et al. 1993; Mortimer 1981). Percutaneous and fully implanted electrodes are placed close to the entry point of the motor
nerve to the muscle which should be stimulated, either epimysial or intramuscular (Cameron et al. 1997; Hoshimiya & Nanda 1989).

Individuals with C5-C7 complete SCI and with no major degree of motoneuron or nerve root damage of the stimulated muscles benefit the most from neuroprosthesis. The use of an implanted FES system can only be applied once the patient reaches stable neurological status, which usually occurs two or more years post SCI. The use of surface FES systems can be introduced during the early rehabilitation period, as the patient does not have to be neurologically stable.

Gorman et al. (1997) and Cornwall and Hausman (2004) have presented guidelines for patient selection for consideration of for an implantable neuroprosthesis. They are as follows:

- Anatomic: Stable tetraplegia with C5 or C6 motor level with international classification motor scores of 0, 1, 2 or an impairment scale level of A, B, C (AIS)
- Physiologic: Presence of adequate ROM in joints of the shoulder, arm, forearm, wrist and hand
- Medical: Free of overwhelming medical problems
- Psychosocial factors: Sufficient motivation to learn its use and use it
- Adequate caregiver and/or family support
- One year post injury, plateau of functional recovery.
- Need for sufficient vision to provide visual feedback during training and use sufficient cognitive ability

Contraindications to neuroprosthesis use include cardiac disease, arrhythmias, pace makers, chronic systemic infections, diabetes, and immune disease

9.1 Types of Neuroprostheses

There are several existing neuroprostheses and these include implanted FES systems such as the Freehand System and the NEC FESMate System and surface stimulation electrode systems such as the NESS H200 (formerly Handmaster NMS-1), Bionic Glove, ETHZ-ParaCare Neuroprosthesis and systems developed by Rebersek and Vodonik (1973) and Popovic et al. (2000).

9.1.1 Freehand System

The Freehand System from Cleveland, OH, USA is an implantable neuroprosthesis intended to restore hand function in C5 and C6 level tetraplegics. The Freehand system can stimulate eight different muscles in order to produce a useful grip and key pinch in tetraplegic individuals. The system consists of a surgically implanted receiver/stimulator unit and electrodes with an external controller and power supply/microprocessor. It was first implanted in 1986 (Cornwall & Hausman 2004). The Freehand System has been implanted in more than 250 individuals with C5 and C6 level tetraplegia (Ragnarsson 2008).

The NeuroControl Freehand System consists of an active receiver/stimulator that is placed in the chest wall and has eight leads that come from the receiver/stimulator and pass under the skin to a connector site in the upper arm. At this point they are joined to epimysial electrode leads that are passed under the skin from the forearm and hand. Power and control signals from the unit are passed through the skin to the receiver/stimulator from a skin-mounted coil. The patient controls the device by movement of the opposite shoulder that uses a skin surface mounted position detector. The lateral grasp is generated by first flexing the fingers to provide
opposition, which is followed by thumb flexion. Palmar grasp is generated by first forming the opposition between the thumb and palm, followed by simultaneous flexion of both the thumb and fingers. Stimulating the flexor digitorum superficialis and profundus muscles performs finger flexion and finger extension is obtained by stimulating the extensor communis digitorum. Stimulation of the thumb thenar’s muscle or median nerve produces thumb flexion. Hand opening and closure strength are proportional to the distance moved by the shoulder. Both palmar and lateral grasps are possible by pressing a button on the shoulder controller. Taylor et al. (2002) and Keith et al. (1996) reported that most clients will require several surgical procedures are needed for each client for optimal use of the device. The most common surgeries performed are brachioradialis to extensor carpi radialis for voluntary wrist extension and posterior deltoid to triceps for elbow extension (Keith et al. 1996; Taylor et al. 2002). The 1st generation of the Freehand System is no longer available from NeuroControl Corporation. There are devices still available on a selective basis in several centres (Cornwall & Hausman 2004; Ragnarsson 2008).

Table 19 Freehand System

<table>
<thead>
<tr>
<th>Author Year Country</th>
<th>Score</th>
<th>Research Design</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wuolle et al. 1999</td>
<td>USA</td>
<td>Case Series</td>
<td>Population: Age=13-53 yr; Gender: males=26, females=8; Level of injury: tetraplegia; Follow-up time=1 yr post survey, including 6 months of home use. Treatment: Implemented with a hand neuroprosthesis that provides grasp and release. Outcome Measures: Functional Evaluations: standardized test of grasp and release (GRT), measurements of pinch strength and range of motion &amp; satisfaction survey.</td>
<td>General Satisfaction: 87% were positive agree or strongly agree, 97% would recommend neuroprosthesis to others, 90% were satisfied with neuroprosthesis, 90% stated neuroprosthesis was reliable, 87% would have surgery again, 80% felt the neuroprosthesis met their expectations, &amp; 77% would pay for the neuroprosthesis if they had the money. Life Impact: 88% responses were positive for life impact; 90% stated neuroprosthesis improved their quality of life; 87% positive impact on their life (90% reported did not make a negative impact); 83% provided a benefit ADL; 87% responses regarding changes in ADL were positive; 93% participants could perform ADL easier; 93% could perform ADL such as painting and shaving; 90% had increased confidence when performing ADL; 83% could perform ADL more normally; 73% could perform ADL faster. Independence: 81% of responses were positive; 87% reported they were able to function more independently; 83% used less adaptive equipment; 87% required less assistance from others; 67% felt more comfortable out in the community alone. Occupation: 57% of responses to occupation questions were positive</td>
</tr>
<tr>
<td>Author Year Country</td>
<td>Score Research Design</td>
<td>Methods</td>
<td>Outcome</td>
<td></td>
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<tr>
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<tr>
<td>Author Year Country</td>
<td>Score Research Design</td>
<td>Methods</td>
<td>Outcome</td>
<td></td>
</tr>
<tr>
<td>Author Year Country</td>
<td>Score Research Design</td>
<td>Methods</td>
<td>Outcome</td>
<td></td>
</tr>
<tr>
<td>Author Year Country</td>
<td>Score Research Design</td>
<td>Methods</td>
<td>Outcome</td>
<td></td>
</tr>
</tbody>
</table>

**Author Year Country**

**Score Research Design**

**Methods**

**Outcome**

5. Appearance: 87% felt their hand appearance was unchanged or improved.

6. Usage: used prosthesis median of 5.5 days/week - ranged from 15 participants (44%) who donned the neuroprosthesis 7 days per week to 5 participants (15%) who used it less than 1 day/week; 24/34 participants (71%) used it 4 or more days/week; range of usage C4/C5, C5/C6, C6/C6 levels was the same (0 to 7 days/week) C5/C6 group - used it most regularly 4 to 7 days/week with most participants 8/10 reporting daily use.

7. Activities: most frequently reported activities included eating, drinking, shaving, brushing teeth, brushing hair, writing, operating a computer, playing games.

8. Quality of Life: 18/34 positive comments; 1/34 responded neutrally; 1/34 responded negatively.

9. Improvements: Additional stimulus channels, an implanted command source, smaller, lighter external control unit - easier to don, improve hand and arm function, make device operable if user is confined to bed.

---

**Carroll et al. 2000**

**Australia**

**Pre-post**

**N=6**

**Population:** Mean age=29.1 yr; Gender: males=4, females=2; Level of injury: tetraplegia; Time since injury=1.2 - 11.3 yr; Chronicity=chronic.

**Treatment:** The Freehand System – an implanted multichannel neuroprosthesis.

**Outcome Measures:** Pinch forces; Grasp and Release Test (GRT); Activities of daily living (ADL) test.

1. There was significant improvement in lateral pinch and palmar grasp force after rehabilitation with and without the neuroprosthesis.

2. Force differences were not found between presurgery and rehabilitation without neuroprosthesis.

3. With neuroprosthesis, subjects could grasp, move and release more items in the 30 second GRT, as compared to without the neuroprosthesis.

4. In 35/48 ADL events, less assistance was used (physically or assistive equipment) with the neuroprosthesis. In 41/48 ADL events, neuroprosthesis use was preferred in all subjects.

5. After study, 5/6 subjects still used neuroprosthesis daily.

---

**Peckham et al. 2001**

**USA/UK/Australia**

**Pre-post**

**N_initial=51; N_final=50**

**Participants:** Age=16-57 yr; Gender: males=42, females=9; Level of injury: C5-C6; Time since injury=4.6 yr; Follow-up time=3-13.9 yr.

**Treatment:** Participants were trained to use the neuroprosthesis and to use it for

1. When the neuroprosthesis was activated all participants increased their pinch force in lateral pinch (p<0.001) and some increased their pinch force in palmar grasp (p<0.001).
<table>
<thead>
<tr>
<th>Author Year Country Score Research Design Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taylor et al. 2001 UK Pre Post N&lt;sub&gt;Initial&lt;/sub&gt;=9; N&lt;sub&gt;Final&lt;/sub&gt;=8</td>
<td>functional activities. Once they were satisfied with their ability to perform daily activities or when they reached a plateau in proficiency then rehab was complete. <strong>Outcome Measures:</strong> Pinch strength, active ROM, Grasp-Release Test, ADL Abilities Test, ADL Assessment Test, user satisfaction survey.</td>
<td>2. 98% of participants moved at least 1 object with the neuroprosthesis (p&lt;0.001) and 37 improved by moving at least 3 more objects (p&lt;0.001). 3. Disability was reduced in 49 of 50 participants as measured by the ADL abilities or ADL assessment tools.</td>
</tr>
<tr>
<td>Memberg et al. 2003 USA Case Series N=22</td>
<td>Population: Age=31-48 yr; Gender: males=7, females=1; Level of injury: C4-6; Time since injury=43-430 months; Follow-up time=8-53 months. <strong>Treatment:</strong> Interviews- reviewing use of Neuro Control Freehand System. <strong>Outcome Measures:</strong> Amount of Care &amp; The System.</td>
<td>1. No statistical results reported 2. Completion of personal care was provided by outside nursing agencies. (mean 11.5 h a day, range 3-24 hrs); 4 users had additional care from family members (mean 3.4 h a day, range 2-5 hrs); no users claimed that care given by family members had decreased 3. System-donning external components 5-10 min; most users reported no significant problems fitting the external equipment; 2 users had problems locating the coil; 3 locating the shoulder controller; 1 had persistent problems maintaining the position through the day due to the adhesive tape used becoming detached (4 reported this as an occasional problem); 4 users had problems with skin allergy to the tape or double sided adhesive rings; 2 users reported that the system made transfers more difficult; 3 users never stopped using the system due to system failure; some problems with equipment reliability; no change in paid caregiver time; 6 users felt more confident when using the system; 7 felt their quality of life had improved.</td>
</tr>
<tr>
<td></td>
<td>Population: Level of injury: C5-C6. <strong>Treatment:</strong> Epimysial or intramuscular electrodes were implanted on the triceps. Following surgery standard stimulation exercise regimens were followed. <strong>Outcome Measures:</strong> elbow extension moments at different elbow positions, performance in controllable workspace experiments, comparison to an alternative method of providing elbow extension in these individuals (posterior deltoid to triceps tendon transfer).</td>
<td>1. Variation in elbow moment across subjects significantly greater than the variance within subjects (ANOVA p&lt; 0.001). 2. 10/11 elbows tested elbow moment generated by triceps stimulation at different elbow angles, elbow moment weakest with elbow in more extended position (30 degrees flexion) and peaked with elbow at 90 flexion, significant ANOVA p&lt;0.001. 3. Elbow moment generated by triceps stimulation at 90 and 120 degrees elbow flexion was significantly greater than elbow moment produced by tendon transfer (ANOVA p&lt;0.05), no difference</td>
</tr>
</tbody>
</table>
### Methods

- **Hobby et al. 2001**<br>**UK**<br>**Pre-post**<br>**N=9**

  **Population:** Age=16-55 yr; Level of injury: tetraplegia.  
  **Treatment:** The patients, using an external stimulator, built up the muscles strength in the hand and forearm, to ensure the muscles were in good condition at the time of surgery.  
  **Outcome Measures:** Grip Strength, ADL.

  1. 7/9 use Freehand System daily.  
  2. Provided an active grip of some strength which allowed many functional activities.  
  3. Increase in self-confidence.  
  4. For over 80% of their selected ADL goals, user preferred to be independent with their Freehand system than use previous method or have activity performed by caregiver.

### Outcome

- **Taylor et al. 2002**<br>**UK**<br>**Case Series**<br>**N=9**

  **Population:** Mean age=38.4 yr; Gender: males=7, females=1; Level of injury: C4-C6; Time since injury=10.1 yr.  
  **Treatment:** None listed. It was an assessment of the Freehand System.  
  **Outcome Measures:** Grasp Release

  1. Grasp release test results: increase in the types of tasks that subjects could perform (pre n=1.4) and post implantation (n=5.1 p=0.011).  
  2. One year post implantation the types of tasks performed was 5.5
<table>
<thead>
<tr>
<th>Author Year Country</th>
<th>Score Research Design</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smith et al. 1994</td>
<td>USA Case Series N=5</td>
<td></td>
<td>Test, Grip Strength, ADLs, Sensory ability (static 2 pt discrimination).</td>
<td>p=0.027, without the system it was 1.2 (p=0.028).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3. Number of repetitions increased post implantation from 12.7 to 37.4 (p=0.028) and without the implant post-implantation (20.2, p=0.046).</td>
<td>4. At one year number of repetitions was increase to 50.5, p=0.046 with the system and without 24.3, p=0.28.</td>
</tr>
<tr>
<td>Bryden et al. 2000</td>
<td>USA Case Series N=4</td>
<td></td>
<td>Population: Age=13-19 yr; Gender: males=5; Level of injury: C5-C6; Time since injury=3-72 months. Treatment: Intramuscular electrodes were implanted in the upper extremity muscles. Outcome measures: The Breslow Test - a non-parametric linear rank test used to compare survival chances across subgroups 95% confidence limit used to reject the null hypothesis.</td>
<td>1. No predicted difference between electrodes in intrinsic and extrinsic muscles (p=0.93).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2. Significant differences were predicted between exit sites (p=0.016) + across muscle groups (p=0.047).</td>
<td>3. Survival likelihoods poorer for electrodes exiting dorsally.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4. At 90 days after implant survivals probabilities of the finger + thumb extensors + thumb abductors were no significant than that of thumb adductor + flexor muscle groups.</td>
<td></td>
</tr>
<tr>
<td>Smith et al. 1996</td>
<td>USA Case Series N=5</td>
<td></td>
<td>Population: Age=13-19 yr; Gender: males=3, females=2; Level of injury: C5; Time since injury=3-72 months. Treatment: FNS vs. Tenodesis. Outcome Measures: CWRU Hand System (Case Western Reserve University), Grasp and Release Test.</td>
<td>1. FNS vs. Tenodesis</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2. With FNS and tenodesis each case of improved performance in later sessions was significantly better as compared to the initial session. (p&lt;0.05).</td>
<td>3. The average grasp forces with FNS increased; the range was from 8.9N (SD+5.2) to 22.5N (SD+8.6) and the palmar grasp forces increases from 2.1N (SD+2.9) to 11.1N (SD+6.0).</td>
</tr>
<tr>
<td>Mulcahey et al. 2004</td>
<td>USA Case Series N=4</td>
<td></td>
<td>Population: Age=13-16 yr; Level of injury: tetraplegia; Time since injury=4-16 weeks. Treatment: The following muscles were</td>
<td>1. No statistical results are reported.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2. No perioperative complications reported.</td>
<td>3. Subjects began Freehand System</td>
</tr>
</tbody>
</table>
Implanted with intramuscular electrodes: Extensor digitorum profundus, extensor pollicis longus, flexor pollicis longus, adductor pollicis, and opponens pollicis for each subject.

**Outcome Measures:** Muscle Strength-Pinch Force & Hand Function, Performance of ADL, Satisfaction with + without the Freehand System (Canadian Occupational Performance Measure (COPM)), Upper Extremity Capacity, Quadriplegic Index of Function.

4. Muscle Strength-no subject gained significant strength in any key muscle on their freehand limb.
5. Pinch Force-with Freehand System - each subject realized significant improvement in pinch force.
6. Upper Extremity Capacity-first 11 questions - no difference with or without Freehand-last set of questions Freehand System improved scores.
7. Quadriplegic Index of Function-all subjects increased their level of independence.

**Note:** ADL=Activities of Daily Living; FNS=Functional Neurostimulation

### Table 20 Summary Implanted Neuroprostheses (Freehand System and CWRU)

<table>
<thead>
<tr>
<th>Author</th>
<th>N</th>
<th>Intervention</th>
<th>Main Outcome(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mulcahey et al. 2004</td>
<td>4</td>
<td>Implanted Freehand System</td>
<td>=UE strength +ve ADL: QIF scores +ve Satisfaction: COPM +ve lateral and palmar pinch =UE capacity: UEC</td>
</tr>
<tr>
<td>Memberg et al. 2003</td>
<td>10</td>
<td>5/11 Implanted Freehand System 6/11 CWRU 6/11 tendon transfer surgery for elbow extension 4 arms triceps electrode 11 triceps electrodes/10 UL</td>
<td>+ve elbow extension +ve workspace assessment</td>
</tr>
<tr>
<td>Taylor et al. 2002</td>
<td>9</td>
<td>Implantation of Freehand System</td>
<td>+ve Grasp Release Test +ve Grip Strength +ve ADL Assessment</td>
</tr>
<tr>
<td>Peckham et al. 2001</td>
<td>51</td>
<td>Implanted Neuroprosthesis and adjunctive surgeries</td>
<td>+ve lateral pinch +ve palmar grasp +ve Grasp Release Test +ve satisfaction =no change in ability and long term stability and function</td>
</tr>
<tr>
<td>Taylor et al. 2001</td>
<td>8</td>
<td>Implantation of Freehand System</td>
<td>=no change in level of personal care assistance -ve system failure +ve ADL and functional use</td>
</tr>
<tr>
<td>Hobby et al. 2001</td>
<td>9</td>
<td>Implanted Freehand System and adjunctive surgeries</td>
<td>+ve ADL and functional use (80%) +ve lateral grasp +ve palmar grasp +ve 5 finger grasp -ve several electrode failures; stimulator failure; medical complications</td>
</tr>
</tbody>
</table>
### 9.1.2 NESS H200 (formerly HandMaster-NMS-1)

The NESS H200 developed by Nathan et al., and produced by Neuromuscular Electrical Stimulator Systems, Ra’anana, Israel is the only commercially available upper limb surface FES system (Ragnarsson 2008). It has been FDA approved for use with stroke patients. It is predominantly used as an exercise tool for stroke subjects and is commercially available in a limited number of countries (Popovic et al. 2002). The NESS H200 has three surface stimulation channels used to generate grasping function in tetraplegic and stroke subjects. One channel is used to stimulate extensor digitorum communis muscle at the volar side of the forearm. The second channel stimulates the flexor digitorium superficialis and profundus muscles. The third stimulation channel generates thumb opposition. The system is controlled with a push button that triggers the hand opening and closing functions. The system is easy to don and doff. However, it does have some limitations in its design. The system is limited by not enough sufficient flexibility to vary the position of the electrodes for stimulation of the finger flexors for grasp; it is a stiff orthosis that fixes the wrist joint angle and prevents full supination of the forearm (Popovic et al. 2002).

### Table 21 NESS H200 (formerly Handmaster-NMS-1)

<table>
<thead>
<tr>
<th>Author</th>
<th>N</th>
<th>Intervention</th>
<th>Main Outcome(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carroll et al. 2000</td>
<td>6</td>
<td>Implanted Freehand System and adjunctive surgeries</td>
<td>+ve lateral pinch and palmar grasp force +ve GRT scores +ve ADL (35/48) activities 5/6 still use the device</td>
</tr>
<tr>
<td>Bryden et al. 2000</td>
<td>4 (5 limbs)</td>
<td>Implantation of Freehand System with electrode to triceps</td>
<td>+ve elbow function (strength, ROM) +ve ADL and functional use</td>
</tr>
<tr>
<td>Wuolle et al. 1999</td>
<td>34</td>
<td>Implanted Freehand System and 31 had adjunctive surgeries</td>
<td>+ve satisfaction (87%) +ve life impact (90%) +ve ADL (87%) +ve independence (81%) +ve occupation (74%) +ve appearance +ve usage (5.5 d/week median) +ve activities +ve QOL</td>
</tr>
<tr>
<td>Kilgore et al. 1997</td>
<td>5</td>
<td>Implanted Neuroprosthesis and adjunctive surgeries</td>
<td>+ve pinch force +ve grasp strength +ve Grasp Release Test +ve ADL and functional use</td>
</tr>
<tr>
<td>Mulcahey et al. 1997</td>
<td>5</td>
<td>Implanted Freehand System and adjunctive surgeries</td>
<td>+ve Grasp Release Test +ve ADL and functional use</td>
</tr>
<tr>
<td>Smith et al. 1996</td>
<td>5</td>
<td>Implanted Neuroprosthesis</td>
<td>+ve unilateral grasp and release abilities with FNS</td>
</tr>
<tr>
<td>Smith et al. 1994</td>
<td>5</td>
<td>Implanted Neuroprosthesis</td>
<td>-ve electrode failure</td>
</tr>
</tbody>
</table>

Note: ADL=Activities of Daily Living; FNS=Functional Neurostimulation; COPM = Canadian Occupational Performance Measure; GRT = Grasp and Release Test; CWRU = Case Western Reserve University + positive outcome; - negative outcome
<table>
<thead>
<tr>
<th>Author Year</th>
<th>Country</th>
<th>Score</th>
<th>Research Design</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
</table>

**Note:** ADL=Activities of Daily Living

### Table 22 Summary NESS H200 (formerly Handmaster-NMS-1)

<table>
<thead>
<tr>
<th>Author</th>
<th>N</th>
<th>Intervention</th>
<th>Main Outcome(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alon &amp; McBride 2003</td>
<td>7</td>
<td>NESS Handmaster</td>
<td>+ve ADL use +ve Grasp Release Test +ve grip strength</td>
</tr>
<tr>
<td>Snoek et al. 2000</td>
<td>10 patients (7 at end)</td>
<td>Handmaster</td>
<td>-ve poor compliance, only 4 completed the training period</td>
</tr>
</tbody>
</table>

+ positive outcome; - negative outcome

#### 9.1.3 Bionic Glove

Developed by Prochazka and colleagues at the University of Alberta the Bionic Glove improves hand function in people with SCI. This device uses three channels of electrical stimulation to stimulate finger flexors, extensors and thumb flexors. The control signal comes from a wrist position transducer mounted in the garment. The actual functioning of the device can be described as greatly augmenting tenodesis (Popovic et al. 2006; Prochazka et al. 1997).

The Bionic Glove is designed to enhance the tenodesis grasp in subjects that have a voluntary control over the wrist (flexion and extension). Stimulates finger flexors and extensors during tenodesis grasp, enhances strength of grasp. The Bionic Glove is available at the University of Alberta, Alberta, Canada and used primarily for clinical evaluation. A modified version of this device will be called Tetron (Popovic et al. 2002).

Overall acceptance rate for long-term use is reported in 30% of potential users. Functions of power grasp and handling of big objects were significantly improved (Popovic et al. 2002). There have been several identified concerns with the device that include damage to the stimulator located on the forearm that is frequently damaged through accidental contact during functional activities and the transducer mechanism is delicate and has to be replaced frequently (Popovic et al. 2001b).
Table 23 Bionic Glove

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Country</th>
<th>Score Level</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Popovic et al.</td>
<td>1999</td>
<td>Yugoslavia</td>
<td>Case Series</td>
<td>N=12</td>
<td>Population: Mean age=26.5 yr; Level of injury: C5-C7; Severity of injury: complete=10, incomplete=12; Length of experience with device=6 months or more. Treatment: Taught how to use the device. Outcome Measures: Quadriplegia Index of Function (QIF); Functional Independence Measure (FIM); Upper Extremity Function Test; Goniometric Measurements.</td>
<td>1. QIF: mean was 19.0±6.5 at the beginning; at the end 28.4±5.2, improvement of 49.5%. 2. FIM: 63.8±10.4 at the beginning; 79.0±8.9 after 6 months. When 3 clients excluded who had 120 points on FIM scores were beginning 44.4±13.5 and 64.8±16.6 after 6 months (increase of 20.4 points/46%). 3. Functional task completion: 6 subjects continued to use the device. On average, 75% of the functions were performed better after 6 months of use. 6/12 (50%) did not continue to use the device. C6-C7 individuals may find the device beneficial enough to use it as an assistive device. 4. Technical improvements, specifically cosmetics, positioning of the electrodes, donning/doffing, should increase the number of regular users. 5. Best candidates are individuals with complete C6-C7 tetraplegia. 6. FIM score between 25-50 (up to 75), QIF between 0-13 (up to 27), are motivated to use it, can demonstrate efficient grasp.</td>
</tr>
<tr>
<td>Prochazka et al.</td>
<td>1997</td>
<td>Canada</td>
<td>Case Series</td>
<td>N=9</td>
<td>Population: Age=22-42 yr; Gender: males=8, females=1; Level of injury: C6-C7; Time since injury=16 months – 22 yr. Treatment: Use of bionic glove. Outcome Measures: Mean peak force of tenodesis grasp, qualitative ratings of manual tasks.</td>
<td>1. Mean peak force of tenodesis grasp in the nine subjects increased from 2.6 N±3.8 N (passive) to 11.3 N±7.4 N (glove active), significant than peak passive force (p=0.0064, t-test), and significant at end of 5th grasp 6.8 N±4.2 N, p=0.0064, Mann-Whitney rank sum test. 2. Most manual tasks improved significantly with the use of the glove.</td>
</tr>
</tbody>
</table>

Table 24 Summary Bionic Glove

<table>
<thead>
<tr>
<th>Author</th>
<th>N</th>
<th>Intervention</th>
<th>Main Outcome(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Popovic et al. 1999</td>
<td>12</td>
<td>Bionic Glove</td>
<td>+ve QIF</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+ve FIM</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+ve UE Function Test</td>
</tr>
<tr>
<td>Prochazka et al. 1997</td>
<td>9</td>
<td>Bionic Glove</td>
<td>+ve grasp</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+ve compliance (60%)</td>
</tr>
</tbody>
</table>

Note: FIM=Functional Independence Measures; QIF=Quadriplegia Index Function + positive outcome; - negative outcome
9.1.4 ETHZ-ParaCare System

The ETHZ-Para Care System was developed collaboratively between ParaCare, the University Hospital Zurich, the Rehabilitation Engineering Group at Swiss Federal Institute of Technology Zurich and Compex SA, Switzerland. The system was designed to improve grasping and walking function in SCI and stroke patients. Surface stimulation FES system is programmable, with 4 stimulation channels and can be interfaced with any sensor or sensory system. The system provides both palmar and lateral grasps. The device has some reported disadvantage that includes a lengthy time to don and doff the device (7-10 minutes) and it is not commercially available. The next generation of the device will be called the Compex Motion (Popovic et al. 2001; Popovic et al. 2006). The Compex Motion device is currently available in clinical trials with approximately 80 units available. The Compex Motion stimulator was designed to serve as a hardware platform for the development of diverse FES systems that apply transcutaneous (surface) stimulation technology. One of the main designs in this system is that it is easily programmable (Popovic et al. 2006).

Table 25 ETHZ ParaCare and Compex Motion Systems

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Country</th>
<th>Score</th>
<th>Research Design</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mangold et al. 2005</td>
<td></td>
<td>Switzerland</td>
<td></td>
<td>Case Series</td>
<td>N=11</td>
<td>Population: Age=15-70 yr; Gender: males=9, females=2; Level of injury: C5-C7; Severity of injury: AIS A-D, FES applied 1-67 mths post injury. Treatment: FES was carried out with a stationary stimulation system and 2 portable systems (ETHZ-Paracare FES system, and Complex Motion). Outcome Measures: videos of functional tasks: hand function tests, self-designed functional tests, f/u query-assessment of muscle strength.</td>
<td>1. Cervical SCI patients can benefit from transcutaneous FES of hand muscles during rehabilitation with respect to muscle strengthening, facilitation of voluntary muscle activity and improvements of ADL functions. 2. Surface FES system is more flexible in its application and does not need surgical procedures. 3. High flexibility in electrode placement, stimulation programmes, and FES control devices is required in order to adapt the system to individual needs.</td>
</tr>
</tbody>
</table>

Note: AIS=ASIA Impairment Scale; FES=Functional Electrical Stimulation

Table 26 Summary ETHZ ParaCare and Complex Motion Systems

<table>
<thead>
<tr>
<th>Author</th>
<th>N</th>
<th>Intervention</th>
<th>Main Outcome(s)</th>
</tr>
</thead>
</table>
| Mangold et al. 2005   | 11        | ETHZ-ParaCare FES System and Compex Motion | +ve Training Programme  
+ve Functional exercises in therapy  
=ADL function in rehab centre  
-ve ADL use at home |

+ positive outcome; =no difference; - negative outcome

9.1.5 Stimulus Router System

The Stimulus Router System (SRS) is an externally controlled neuroprosthesis that has only one component implanted (passive lead, pick-up terminal) under the skin and the other end (delivery terminal) is tunneled to a target nerve. A surface electrode is placed over the implanted pick-up terminal and a second electrode is placed nearby. Current pulses are passed through the skin between the electrodes. The basic properties of the SRS were explored in two animal experiments (Gan et al. 2007; Gan & Prochazka 2010) which showed that the SRS was reliable as a long term neuroprosthesis and was able to selectively activate deep-lying nerves in a
graded manner over the full physiological range. A case study of the first implant of the SRS in a person with tetraplegia with bilateral hand paralysis was completed (Gan et al. 2012) which showed initial success of the system.

9.2 Other Surface or Percutaneous Neuroprosthesis Systems

9.2.1 NEC-FES System

The Sendai FES team in corporation with NEC Inc. 1994 developed the NEC-FES System. The system is to restore both grasping and walking abilities. It is an implanted FES system with 16 stimulation channels. It is used almost exclusively for research purposes and is not available outside Japan.

9.2.2 Rebersek and Vodovik (1973) Neuroprosthesis

This is one of the first FES systems developed for grasping three decades ago. The device has three stimulation channels (2 stimulation electrodes per channel) that are used to generate the grasping function by stimulating finger flexors and extensors and thumb flexors. The user can control the stimulation intensity via different sensory interfaces such as EMG sensor, sliding resistor and pressure sensors. The main reported disadvantages of the system are the long donning and doffing times and the selectivity of stimulation is low. This device is not commercially available (Popovic et al. 2001).

9.2.3 Belgrade Grasping-Reaching System

The Belgrade Grasping-Reaching System (BGS) as proposed by Popovic et al. (1998) is a neuroprosthesis device designed for grasping and it also provides a reaching function. The device has four stimulation channels (three for generating grasping function and fourth to stimulate triceps brachii muscle for elbow extension). The grasping function is controlled via a push button that triggers hand opening and closing. The motion of grasp is performed in three phases; prehension that forms the correct aperture of the hand, a relaxation phase that allows the hand to get into good contact with the object and closure of the hand by opposing either the palm and the thumb or side of index finger and thumb. The act of hand release is completed in two stages; opening of the hand and resting. Measuring the subject's shoulder velocity with a goniometer and then generating a synergistic elbow motion by stimulation of the triceps brachii muscle achieves the reaching function of the upper limb. It is reported that the BGS system requires more time to place electrodes compared to Handmaster system, and it is not commercially available (Popovic et al. 2002).

9.3 Reported Benefits of Neuroprosthesis Use

There have been many documented and reported benefits of neuroprosthesis use with the spinal cord injured person. The training required to use the device leads to short and long-term changes within the CNS(Popovic et al. 2002). A neuroprosthesis can be used as a neurorehabilitation system that promotes recovery and better hand function in incomplete SCI and stroke subjects or as a permanent orthotic device for complete cervical lesion SCI subjects to augment the grasp and manipulation functions required for typical ADLs.

9.4 Clinical Results of Neuroprosthesis Use

The following are the reported clinical results of neuroprosthesis use;
- Clinical trials show improvement in grasping functions in stroke and SCI subjects
- FES technology facilitates a comfortable and secure grasp that allows the individual to hold and manipulate various objects
• All except the Bionic Glove were able to facilitate both palmar (power) grasp and lateral (fine) grasp
• The Handmaster-NMS-1, the BGS system, and the ETHZ-ParaCare neuroprostheses have been applied successfully as rehabilitation tools to restore grasping function in SCI individuals instead of being used as permanent orthotic systems
• To control the neuroprosthesis, subjects are using either an on-off type of switch or have to apply simple analog sensors to generate desired control commands
• There is a delay of 1-2 seconds from time command is issued and moment that grasp is executed which restricts the speed that an individual can grasp and release objects
• Neuroprosthesis for grasping can only be used for slower grasping tasks
• The most widely used and accepted neuroprostheses for grasping are the Freehand System and the Handmaster-NMS-1 and all of the other neuroprostheses mentioned are mainly used in experimental trials for research purposes.

9.5 Challenges in Neuroprosthesis Use

There are several reported challenges in neuroprosthesis use:
• There is a general perception within the clinical community that neuroprosthesis technology is not fully matured and the application of its use is labour intensive
• Patients and families have over expectations from assistive systems as aspirations and results do not match
• Acceptance of the device depends on the specific needs of the client
• Complicated by variety of age and lifestyle factors represented in patients with UE paralysis
• Complacent (feel comfortable, safe and happy with home and workplace adaptation and with attendant care)
• Waiting for cure (refuse any other intervention)
• Afraid of technology
• Degree of cognitive interaction they require – high levels of attention to their neuroprosthesis may interfere with social interaction
• Impact in clinical applications is limited
• Reasons for poor acceptance are that it can be technical, cultural and psychological
• FES technology requires intensive maintenance and skilled technician
• Found to be effective in hospitals with strong engineering support
• Attempts to simplify neuroprosthesis systems and reduce the system’s donning and doffing time resulted in less technical support needed but the devices then failed to address the needs of a wider population
• Inadequate reliability of use (breakage of wires, electrode failure, accidental damage)
• The grasping functions are robotic quality of stimulated motions and in order to design a more dexterous hand motion it would require a more complicated system
• Overall cosmetics of the device
• Implanted neuroprosthesis require additional surgery and it is recommended that tendon transfers be performed to augment the system
• Extensive training is required to learn how to use the device, which is expensive in terms of staffing and resources
• Efforts to increase reliability of system components, data on long-term reliability not yet available
• Simple systems for powered tenodesis grip for individual with lesions at C6 or lower have not been fully explored in deference to volditional tendon transfer surgery (Popovic et al. 2002; Triolo et al. 1996)
Discussion

The use of neuroprosthesis whether implanted or surface electrodes appear to benefit persons with C5-C7 level tetraplegia. The studies consistently demonstrate improvements in pinch (lateral and palmar), grip strength, and ADL functioning and general satisfaction with the use of the device, although the study subject numbers are relatively small. Ongoing compliancy and use of the devices on a long-term basis continue to be problematic. Reasons for discontinuing the use of the device are with length of time and the amount of assistance required to don and doff the device, and if using the device can provide enough of a difference in overall level of functioning. The studies also consistently report both mechanical/electrode failure and adverse medical complications. Many of the devices are only available in specialized rehabilitation centres where access to rehabilitation engineering is available. In addition, many of the devices continue to be only available in clinical trials. The overall cost to use the device continues to be great when factors such as cost of the device, the extensive training period required and staff to support the programme. The next generation of implantable FES devices are being developed at the FES Centre in Cleveland, OHIO and The Shriner’s Hospital, Philadelphia, Pennsylvania. These are internally powered and wirelessly control, eliminating an external coil and control unit. Also, in Alberta, Canada the ReJoyce System by Prochazka et al. (1997) a surface FES system and the SRS is being tested and further developed.

Conclusion

There is level 4 evidence (see Table 19-26) that support the use of neuroprostheses for persons with C5-C6 complete tetraplegia in the improvement of pinch and grip strength and ADL functioning. However, many devices are only available in clinical trials in specialized rehabilitation centres and the overall cost of the device continues to be expensive.

The use of neuroprostheses appears to have a positive impact on pinch and grip strength and ADL functions in C5-C6 complete tetraplegia, however, access to the devices are limited and continue to be expensive in use.

9.6 Second Generation Neuroprosthesis: Myoelectrically Controlled

Second generation of neuroprosthesis (NP) being developed at Case Western Reserve, Cleveland, OH, USA, provides control of grasp, forearm pronation and elbow extension through the use of electromyographic signals generated by voluntary musculature used to control the various functions of the NP. The system consists of an implanted stimulator-telemeter (IST-12), implanted electrodes for stimulation and recording, an external control unit and a transcutaneous inductive link. The EMG signals can be obtained from two independent muscles. The IST-12 is capable of stimulating 12 different muscles. The design feature of the IST-12 enables the size of the implanted components to remain small and provides the opportunity for customized control algorithms and stimulation patterns. The NP functions controlled via EMG signal includes grasp pattern selection (2-4 grasp patterns), opening and closing the hand in a proportional manner, turning the system on and off, turning elbow extension on and off, and the ability to lock and unlock the hand so that the grasp can be maintained in a fixed position without the need for continued control input. One EMG channel is used to control grasp opening and closing and is generally placed on the most distal UE muscle.
under voluntary control, typically the extensor carpi radialis longus (ECRL) and brachioradialis (Br). The second EMG channel is used to provide state or logic commands such as system on/off and selection of grasp pattern. The latter channel is placed on a more proximal muscle such as trapezius and platysma. All of the control signals are derived from ipsilateral muscles, enabling bilateral function to be provided by implementing a second system in the contralateral limb (Kilgore et al. 2008).

Augmentive surgical procedures (arthrodeses, tendon transfers and tendon synchronization using side by side repair) to the hand and arm are often performed at the same time of the implantation to provide improved hand function when the IST-12 is not being used and to further optimize the system with electrically stimulated transfers (Kilgore et al. 2008).

Further research is also being completed on an implantable stimulator and wearable external controller (Micropulse) at the Cleveland FES Centre, Cleveland, USA. The controller, under going benching testing, is worn on the wrist and wirelessly communicates with the implantable stimulator (Wheeler & Peckham 2009).

Another device being developed is the myoelectrically controlled functional electrical stimulation (MeCFES) in Denmark. This system consists of an amplifier, a signal processor and single-channel stimulator that allows the user to proportionally control the stimulus intensity to reinforce the tendosis grip in subjects with C6-7 tetraplegia.

Table 27 Second Generation Neuroprosthesis: Myoelectrically Controlled

<table>
<thead>
<tr>
<th>Author Year Country Score Research Design</th>
<th>Methods</th>
<th>Outcome</th>
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<tr>
<td>Kilgore et al. 2008 USA Pre-post N=3</td>
<td>Population: Age=24, 34, 43 yr; Level of injury: C5=1, C6=2; Time from injury to implant=1, 2, and 4 yr. Treatment: A second generation neuroprosthesis system was implanted into individuals and functional outcomes were evaluated. Outcome Measures: Grasp and Release Test, Activities of Daily Living Abilities (ADLAT), Craig Handicapped Assessment and Reporting Tool (CHART) and the NP Usage Survey.</td>
<td>1. Functional Outcomes: all 3 subjects used their NP to perform activities that they could not perform prior to implantation (post implant follow up ranged from 2-4 years). 2. Body Structures and Function: every subject improved in pinch force strength; post op pinch force with the NP was significantly greater than without the NP (paired-sample t-test, p=.038). 3. Activities: every subject was able to double the number of objects manipulated in the GRT with NP (2 subjects completed 6/6 tasks; one subject 5/6 tasks) 4. ADLAT all 3 subjects improved in least 5 activities with one subject in all 9. 5. Participation: all 3 subjects increased their scores for physical independence, 1 in the mobility task, 1 in the social integration scale, 1 subject a decrease in occupation subscale. 6. Device Usage: 2/3 reported daily usage of the NP; 1/3 used the device 50% of the time</td>
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Note: GRT=Grasp and Release Test; NP=Neuroprosthesis
The study by Kilgore et al. (2008) studied the first three individuals to receive a myoelectrically controlled NP (IST-12) designed for hand and arm function. The IST-12 can stimulate 12 different muscles versus the first generation NP (Freehand System) which only stimulated 8 muscles. The additional electrodes provided the user with improved hand function (activation of the intrinsic muscles), wrist extension, improved reach (triceps function) and improved shoulder stability through activation of the shoulder musculature. The IST-12 provided each of the three subjects with significantly increased pinch force and grasp function which resulted in increased independence with ADL functions. All three study subjects used the device at home on a regular basis. The durability of the implanted components was comparable to long-term results from the first generation NP, an incidence failure of<2%.

Conclusion

_There is level 4 evidence (from one pre-post study; Kilgore et al. 2008) that the use of the IST-12, a second generation neuroprosthesis, combined with augmented surgical procedures (arthrodesis, tendon transfers and tendon synchronization) improved pinch force, grasp function and the functional abilities of individuals with cervical level spinal cord injuries._

The IST-12 neuroprosthesis, a second generation, myoelectrically controlled implantable device appears to have a positive effect on pinch and grasp functions which result in increased independence with activities of daily living.

9.7 Miscellaneous

Research into brain-machine interfaces is beginning to be published. Brain-machine interface is based on the concept of translating neural activity into control of an external device with the capability of producing natural movements. Just one study has been published which examined two 96-channel intracortical microelectrodes implanted into the motor cortex of a patient (Collinger et al. 2013).

Finally, there have been initial studies on exoskeleton robots (controlled by electromyographical signals (EMGs) of the user) (Ueda et al. 2010), the five degree of freedom user command controller (Scott & Vare 2013) and the use of robotic training for improving hand and upper limb control (Cortes et al. 2013; Zariffa et al. 2012b).
The treatment and management of the upper limb in persons with a SCI can be rewarding yet very challenging. Secondary complications related to repetitive strain injury, pain and hypertonicity in addition to aging presents numerous challenges for both the injured individual and the clinician. In reviewing the critical evidence of treatment interventions it was surprising that there were few studies on the effectiveness of traditional interventions such as strengthening, exercise, splinting and management of hypertonicity. The majority of research for the upper limb has been focused on reconstructive surgery and the use of neuroprosthesis. Advancements in understanding the mechanisms related to SCI has led to restorative treatment interventions especially in the management of the incomplete SCI person.

This chapter outlined the importance in the prevention of upper limb dysfunction and the impact of an injury in one’s overall level of basic independence in the areas of self-care and mobility. Further research and consensus is needed in how we assess and document upper limb function especially hand function in an effort to establish objective, reliable and measurable outcomes. Other areas for further research have been identified throughout the chapter.

There is level 2 evidence (from one randomized controlled trial; Hicks et al. 2003) that physical capacity continues to improve after 1-year post discharge.

There is level 1b evidence (from one randomized controlled trial; Needham-Shrophire et al. 1997) that neuromuscular stimulation-assisted exercise improves muscle strength over conventional therapy.

There is level 4 evidence (from one case series study; Cameron et al. 1998) that neuromuscular stimulation-assisted ergometry alone and in conjunction with voluntary arm crank exercise was an effective strengthening intervention for chronically injured individuals.

There is level 4 evidence (from one pre-post study; Drolet et al. 1999) that muscle strength continues to improve up to 15 months post hospital discharge for both tetraplegic and paraplegic individuals.

There is level 1a evidence (from two randomized controlled trials; Kohlmeyer et al. 1996; Popovic et al. 2006) that augmented feedback is not effective in improving upper limb function in tetraplegia.

There is level 4 evidence (from one case series study; Burns & Meythaler 2001) that intrathecal baclofen may be an effective treatment for upper extremity hypertonia of spinal cord origin.

There is level 1a evidence (from two randomized controlled trials; Bekkhuizen & Field-Fote 2005, 2008) that showed that massed practice (repetitive activity) and somatosensory stimulation (median nerve stimulation) demonstrated significant improvement in upper extremity function, grip and pinch strength required for functional activity use.

There is level 4 evidence (from one pre-post study; Belci et al. 2004) that showed that rTMs treatment in individuals with chronic stable ISCI may produce reductions in
corticospinal inhibition that resulted in clinical and functional changes for several weeks after treatment.

There is level 2 evidence (from one randomized controlled trial; Wong et al. 2003) that showed that the use of concomitant auricular and electrical acupuncture therapy may improve the neurological and functional recovery of acute spinal cord injured individuals.

There is level 2 evidence (from one randomized controlled trial; DiPasquale-Lehnerz 1994) that wearing a thumb opponens splint will improve pinch strength and functional use of the hand.

There is level 1b evidence (from one randomized controlled trial; Harvey et al. 2006) that 12 weeks of nightly stretch with a thumb splint did not reduce thumb web-space contractures in persons with a neurological condition (i.e., stroke, ABI, SCI).

There is level 1b evidence (from two randomized controlled trials; Hicks et al. 2003; Curtis et al. 1999) that a shoulder exercise and stretching protocol reduces the intensity of shoulder pain post SCI.

There is level 1b evidence (from one randomized controlled trial; Dyson-Hudson et al. 2001) that general acupuncture is no more effective than Trager therapy in reducing post-SCI upper limb pain. There is level 4 evidence (see Table 9-18) that support the use of reconstructive surgery for the tetraplegic upper limb for the improvement of ADL and quality of life.

There are only a few reported and published studies on nerve transfer surgery for restoring hand and upper limb function after a SCI and based on the published literature, nerve transfer surgery is emerging as another surgical alternative.

There is level 4 evidence (see Table 19-26) that support the use of neuroprostheses for persons with C5-C6 complete tetraplegia in the improvement of pinch and grip strength and ADL functioning. However, many devices are only available in clinical trials in specialized rehabilitation centres and the overall cost of the device continues to be expensive.

There is level 4 evidence (from one pre-post study; Kilgore et al. 2008) that the use of the IST-12, a second generation neuroprosthesis, combined with augmented surgical procedures (arthrodesis, tendon transfers and tendon synchronization) improved pinch force, grasp function and the functional abilities of individuals with cervical level spinal cord injuries.
References


