Upper Limb Rehabilitation Following Spinal Cord Injury

Danielle Rice PhD (c)
Pavlina Faltynek P MSc
McIntyre A MSc RN
Swati Mehta PhD
Brianne Foulon HBA
Robert Teasell MD FRCPC
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.
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**Abbreviations**

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<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AbINT</td>
<td>Activity based Intervention</td>
</tr>
<tr>
<td>ADL</td>
<td>Activities of Daily Living</td>
</tr>
<tr>
<td>AIS</td>
<td>ASIA Impairment Scale</td>
</tr>
<tr>
<td>AP</td>
<td>Action Potential</td>
</tr>
<tr>
<td>APB</td>
<td>Abductor Pollicis Brevis</td>
</tr>
<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>
</tr>
<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>
</tr>
<tr>
<td>CPG</td>
<td>Central Pattern Generators</td>
</tr>
<tr>
<td>CSF</td>
<td>Cerebrospinal Fluid</td>
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<tr>
<td>Cu-</td>
<td>Cutaneous</td>
</tr>
<tr>
<td>CWRU</td>
<td>Case Western Reserve University</td>
</tr>
<tr>
<td>ECRB</td>
<td>Extensor Capri Radialis Brevis</td>
</tr>
<tr>
<td>ECRL</td>
<td>Extensor Capri Radialis Longus</td>
</tr>
<tr>
<td>EDM</td>
<td>Extensor Digiti Minimi</td>
</tr>
<tr>
<td>EMG</td>
<td>Electromyography</td>
</tr>
<tr>
<td>FCR</td>
<td>Flexor Carpi Radialis</td>
</tr>
<tr>
<td>FDP</td>
<td>Flexor Digitorum Profundus</td>
</tr>
<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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<tr>
<td>FIM</td>
<td>Functional Independence Measure</td>
</tr>
<tr>
<td>fMRI</td>
<td>Functional Magnetic Resonance Imaging</td>
</tr>
<tr>
<td>FNS</td>
<td>Functional Neurostimulation</td>
</tr>
<tr>
<td>FPL</td>
<td>Flexor Pollicis Longus</td>
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<tr>
<td>FVC</td>
<td>Forced Vital Capacity</td>
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<tr>
<td>GRT</td>
<td>Grasp and Release Test</td>
</tr>
<tr>
<td>HHD</td>
<td>Handheld Dynamometry</td>
</tr>
<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>
</tr>
<tr>
<td>MP</td>
<td>Massed Practice</td>
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<tr>
<td>MRCS</td>
<td>Medical Research Council Scale</td>
</tr>
<tr>
<td>MRI</td>
<td>Magnetic Resonance Imaging</td>
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<tr>
<td>NMS</td>
<td>Neuromuscular Stimulation</td>
</tr>
<tr>
<td>NP</td>
<td>Neuroprothesis</td>
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<tr>
<td>NRS</td>
<td>Numeric Rating Scale</td>
</tr>
<tr>
<td>O-</td>
<td>Ocular</td>
</tr>
<tr>
<td>OT</td>
<td>Occupational Therapy</td>
</tr>
<tr>
<td>PC</td>
<td>Performance Corrected</td>
</tr>
<tr>
<td>PD</td>
<td>Posterior third of the deltoid</td>
</tr>
<tr>
<td>PET</td>
<td>Positron Emission Topography</td>
</tr>
<tr>
<td>PO</td>
<td>Power Output</td>
</tr>
<tr>
<td>PT</td>
<td>Physiotherapy</td>
</tr>
<tr>
<td>PT</td>
<td>Pronator Teres</td>
</tr>
<tr>
<td>PVA</td>
<td>Paralyzed Veterans of America</td>
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<tr>
<td>QIF</td>
<td>Quadriplegic Index Function</td>
</tr>
<tr>
<td>REL</td>
<td>Rehabilitation Engineering Laboratory Hand Function Test</td>
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<tr>
<td>Acronym</td>
<td>Full Form</td>
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<tr>
<td>---------</td>
<td>-----------</td>
</tr>
<tr>
<td>ROM</td>
<td>Range of Motion</td>
</tr>
<tr>
<td>rTMS</td>
<td>Repetitive Transcranial Magnetic Stimulation</td>
</tr>
<tr>
<td>SCI</td>
<td>Spinal Cord Injury</td>
</tr>
<tr>
<td>SCIM</td>
<td>Spinal Cord Independence Measure</td>
</tr>
<tr>
<td>SEM</td>
<td>Standard Error of Mean</td>
</tr>
<tr>
<td>SRS</td>
<td>Stimulator Router System</td>
</tr>
<tr>
<td>SS</td>
<td>Somatosensory Peripheral Nerve Stimulation</td>
</tr>
<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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</tbody>
</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 or loss 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 one’s 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). Elderly patients with SCI also have greater activity-related deficits than younger patients with SCI (Wirz et al., 2015).

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 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. These findings did not differ by gender or number of years post SCI which suggests that recovering even partial arm and hand function may have a significant impact on the independence of many spinal cord individuals (Anderson et al., 2004).
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. Bryden et al. (2005) proposed a similar hierarchy of upper extremity functional restoration for individuals with tetraplegia including 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 management and care of the upper limb can relate to the phase of upper limb rehabilitation, which has been divided into three phases, including the: acute, subacute, and reconstructive phase (Murphy and Chuiard 1998). 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 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.

There is no consensus regarding the management of the tetraplegic upper limb, this may be due to the variations in muscle function after a SCI (Thomas et al., 2014). Understanding the diversity of a SCI is important in ensuring that therapy is tailored to each individual and that feedback is elicited from patient’s regarding their perceptions of the usefulness of specific interventions (Thomas et al., 2014). Hummel et al. (2005), Snoek et al. (2005) and the Consortium for Spinal Cord Medicine (2005) provide excellent recommendations as a starting point for the management of the tetraplegic upper limb.

There is agreement that restoration of hand function is an important goal in rehabilitation. It is also worth noting that there are few upper extremity tests that accurately evaluate upper limb function in this population (van Tuijl et al., 2002). Curtin (1994) and Krajinik and Bridle (1992) noted a great inconsistency in evaluation and documentation of the tetraplegic upper limb between therapists. The initial upper-extremity motor score (UEMS) in combination with ulnar compound motor action potentials (CMAP) is one set of measures that can serve as early predictors of ADL outcomes and sensorimotor deficit after injury (Wirz et al., 2015).

Several studies have explored increased hand function as a result of reconstructive surgery and/or neuroprosthesis. Although these, and many other treatment options exist, and can improve the overall functioning and functional independence of the person with tetraplegia, 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 persons with tetraplegia 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 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 to perform reconstructive surgeries.

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 reporting on the presence of muscle synergies that involve a motor control paradigm 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 are 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 that 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. No clear relationship was found between the functional abilities of subjects with SCI and those subject deviations 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 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.

#### Table 1 Acute Phase of Rehabilitation

<table>
<thead>
<tr>
<th>Author Year</th>
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<th>Research Design</th>
<th>Score</th>
<th>Total Sample Size</th>
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<tbody>
<tr>
<td>Rice et al. 2014 USA RCT PEDro=8 N=93</td>
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</table>

**Population:** Intervention Group (IG; n=12): Mean age: 33.2±14.3 yr; Gender: males=9, females=3; Level of injury: paraplegia=12, tetraplegia=0; AIS level: A=6, B=1, C=3, D=1, Not rated=1. Standard Care Group (SCG; n=25): Mean age: 40.8±16.4 yr; Gender: males=19, females=6; Level of injury: paraplegia=22, tetraplegia=3; Severity of Injury: AIS A=14, ASI B=3, AIS C=5, AIS D=1, N/R=2.

**Intervention:** All participants were independent manual wheelchair (MWC) users. The intervention group was strictly educated on the Paralyzed Veterans of America’s Clinical Practice Guidelines (CPG) for Preservation of Upper Limb Function by a physical therapist and an occupational therapist in an inpatient rehabilitation facility. The standard of care group received standard therapy services.

**Outcome Measures:** Comparison of wheelchair setup, selection, propulsion biomechanics, Numeric Rating Scale (NRS), Wheelchair Users Shoulder Pain Index (WUSPI), and Satisfaction With Life Scale (SFWL), Craig Handicap Assessment and Reporting Technique (CHART) scores.

1. In wheelchair setup, no significant interaction, between-subject differences, or within subject differences were found between study groups (p>0.05).
2. Although differences were not significant, the percentage of IG participants within the guideline recommendation increased by 25% while the percentage of SCG participants within the guideline recommendation decreased by 5%.
3. No significant differences were found between groups in wheelchair selection (p>0.05); however, 100% of the IG participants had an ultralight MWC at 6mon and 1 yr compared with 68.8% (6 mon) and 77.8% (1Y) of the SCG participants.
4. IG propelled with a significantly lower push frequency than the SCG on tile (p<0.02) and on a ramp (p<0.03) but not carpet (p=0.10).
5. No significant differences were found between NRS or WUSPI scores in the IG and SCG (p>0.05).
6. A simple main effect trend (p=0.07) found that the IG had an increase in the CHART physical subsection scores between 6-mon and 1 yr and an increase in the occupational subsection.
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<th>Author Year</th>
<th>Country</th>
<th>Research Design</th>
<th>Score</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
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</table>

**Effect Sizes:** Forest plot of standardized mean differences (SMD±95%C.I.) as calculated from pre- and post-intervention data.

Discussion

Rice et al. (2014) tested the efficacy of providing education of the PVA Clinical Practice Guidelines for Preservation of Upper Limb Function among manual wheelchair users. This RCT compared education to standard care among individuals with new SCI and found that receiving education resulted in better wheelchair skills including improved push frequency and length.

Rice et al. (2014) recommended further research in this area to:
• Determine if differences in propulsion skills result in decreased pain and improved quality of life.
• Determine if improvements are maintained over the long-term.

Conclusions

There is level 1b evidence (from one randomized controlled trial; Rice et al., 2014) that education improves wheelchair skills after 1 year post discharge.

Providing education to manual wheelchair users is effective in improving the push frequency and push length while using a wheelchair.

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 (Haism et al., 2006). The inability to reach one’s maximum potential can 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 decreased activity and functioning (Haisma et al., 2006). With shorter length of stay in hospital, individuals with a SCI have fewer in hospital rehabilitation opportunities.

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 post-SCI and muscle strength is identified as an important contributor to functional independence (Drolet et al., 1999). Studies by Noreau et al. (1993), Marciello 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 two and eight 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 (two-four weeks) might be explained by improved capacity to recruit motor units (neural adaptation), and gains observed after four 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 2 Exercise and Strengthening

<table>
<thead>
<tr>
<th>Author Year Country</th>
<th>Research Design</th>
<th>Score</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hicks et al., 2003</td>
<td>RCT</td>
<td>PEDro=5</td>
<td>$N_{\text{Initial}}=34; N_{\text{Final}}=11$</td>
<td><em>Population:</em> Age: 19-65 yr; Level of injury: C4-L1; Severity of injury: AIS A-D; Time since injury: 1-24 yr. <em>Intervention:</em> Experimental group (EX) participated in progressive exercise training twice weekly for nine mo-each session offered on alternative days lasing 90-120 min. <em>Outcome Measures:</em> Perceived stress scale, Muscle strength, Depression, Physical self-concept pain, Perceived health, Quality of Life (QoL).</td>
<td>1. Overall 11 in the EX group (exercise adherence 82.5%) and 13 in the control group completed the study. 2. No differences were noted between the two groups at baseline. 3. Following training, EX group had significant increases in sub maximal arm ergometry power output (81%; $p&lt;0.05$) and significant increases in upper body muscle strength (19-34%; $p&lt;0.05$). 4. 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 ($p&lt;0.05$).</td>
</tr>
</tbody>
</table>

Effect Sizes: Forest plot of standardized mean differences (SMD±95%C.I.) as calculated from pre- and post-intervention data.
Hicks et al. 2003; Exercise Training

**Author Year Country**

<table>
<thead>
<tr>
<th>Research Design</th>
<th>Score</th>
<th>Total Sample Size</th>
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</thead>
<tbody>
<tr>
<td>Needham-Shrophire et al., 1997</td>
<td>USA</td>
<td>RCT</td>
</tr>
<tr>
<td><strong>Population</strong>: Age: 18-45 yr; Gender: males=31, females=3; Level of injury: tetraplegia; Mean time since injury: 3 yr.</td>
<td><strong>Intervention</strong>: 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.</td>
<td><strong>Outcome Measures</strong>: Manual muscle test.</td>
</tr>
<tr>
<td>1. No significant difference was found at the four-week evaluation between Groups 1 and 2 (p=0.22) or between Groups 2 and 3 (p=0.07).</td>
<td>2. Subjects in Group 1 had a higher proportion of muscles improving one or more muscle grades after four weeks of NMS cycling compared with Group 3 (p&lt;0.003).</td>
<td>3. Following the second four weeks of training, a significant difference was found between Groups 1 and 3 (p&lt;0.0005) and between Groups 2 and 3 (p=0.03).</td>
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<tr>
<td>4. No statistical difference was found between Groups 1 and 2 (p=0.15).</td>
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**Author Year Country**

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<thead>
<tr>
<th>Research Design</th>
<th>Score</th>
<th>Total Sample Size</th>
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<tbody>
<tr>
<td>Bunday et al. 2014</td>
<td>USA</td>
<td>Prospective Controlled Trial</td>
</tr>
<tr>
<td><strong>Population</strong>: SCI population (n=23): Mean age: 51.9±11.8 yr; Gender: males=21, females=2; Level of injury: C2-C8=23; Severity of Injury: AIS-A=2, AIS-B=1, AIS-C-D=2. Age matched controls (n=20): Mean age: 45±16.2 yr; Gender: males=8, females=12.</td>
<td><strong>Intervention</strong>: Participants performed tasks requiring precision grip and index finger abduction while noninvasive cortical and cervicomedullary stimulation allowed motor evoked potentials (MEPs). The activity in intracortical and subcortical pathways were examined.</td>
<td><strong>Outcome Measures</strong>: EMG activity, F-wave amplitude and persistence, Suppression of voluntary EMG by subthreshold TMS (svEMG).</td>
</tr>
<tr>
<td>1. Significant effect of group (p=0.001) but not task (p=0.21) or interaction (p=0.19) on FDI mean rectified EMG activity.</td>
<td>2. EMG activity increased in SCI patients taking baclofen (SCIBac) (p=0.001) and patients who never took baclofen (SCINo-Bac) (p=0.01) compared with controls; no significance between patient groups (p=0.95).</td>
<td>3. Both SCI and control groups maintained similar EMG activity in the FDI muscle during precision grip and index finger abduction (p=0.21).</td>
</tr>
</tbody>
</table>
| 4. During index finger abduction, controls (p=0.01), SCIBac (p<0.001) and SCINo-Bac (p=0.04) more EMG activity in FDI compared to APB at
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<tr>
<th>Author Year Country</th>
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<th>Methods</th>
<th>Outcome</th>
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<tr>
<td>Haisma et al., 2006 Netherlands Prospective cohort N\textsubscript{Initial}=186; N\textsubscript{Final}=42</td>
<td></td>
<td>Population: Mean age: 40 yr; Gender: males=140, females=46; Level of injury: paraplegia, tetraplegia; Severity of injury: complete=125, incomplete=61; Mean time since injury: 105 d. Intervention: Assessments were taken at four time points: start of inpatient rehabilitation; three months later; discharge and at one year after discharge. Outcome Measures: Power output (PO) peak, VO\textsubscript{2} peak, strength of upper extremity, respiratory function.</td>
<td>all Transcranial magnetic stimulation (TMS) intensities. 5. Significant decrease in MEP size in controls (p&lt;0.001) and SCI\text{Bac} (p=0.001) during precision grip compared with index finger abduction. 6. At increasing stimulus intensities, MEP sizes in control subjects were significantly larger than SCI\text{No-Bac} and SCI\text{Bac} (p&lt;0.001). 7. FDI cervicodorsal MEPs decreased during precision grip compared with index finger abduction in controls (p&lt;0.01) and SCI\text{Bac} (p&lt;0.01) but not SCI\text{No-Bac} (p=0.57). 8. No effect of task, group or their interaction on F-wave amplitude or F-wave persistence (p&gt;0.05). 9. Significant effect of task (p&lt;0.001), but not group (p=0.39) or their interaction (p=0.20) on svEMG. 10. Significant decrease in svEMG area during precision grip compared with index finger abduction in controls (p=0.03), SCI\text{Bac} (p=0.02) and SCI\text{No-Bac} (p=0.02).</td>
</tr>
<tr>
<td>Drolet et al., 1999 Canada Pre-post N\textsubscript{Initial}=40; N\textsubscript{Final}=31</td>
<td></td>
<td>Population: Mean age: 29.5 yr; Gender: males=27, females=4; Level of injury: paraplegia=18, tetraplegia=13; Severity of injury: AIS A-D; Mean time since injury: 2 mo; Mean length of stay: 4.5 mo. Intervention: Rehab included physiotherapy (PT), occupational therapy</td>
<td>1. Age was related to the PO peak and handheld dynamometry (HHD) score (p&lt;0.05), the older the subject the more improvement in either of these measures was significantly less than it was in younger subjects. 2. Men had greater PO peak, VO\textsubscript{2} peak and HHD score than women did (p&lt;0.05), thus improvement in men was greater than women. 3. In tetraplegia subjects the PO peak, VO\textsubscript{2} peak, muscle strength and % of forced vital capacity (FVC) was lower (p&lt;0.05) than it was in paraplegia subjects, but tetraplegia subjects improved more in muscle strength and % of forced expiratory flow (FEV1). 4. Those with a complete lesion had greater HHD score and lower % of FVC than those with incomplete lesions (p&lt;0.05). 5. Strength values at admittance were inversely repeated to strengthen changes during rehab (Pearson correlation coefficients ranging from -0.47 (p=0.001 shoulder flexors) to -0.73 (p&lt;0.001 shoulder adductors).</td>
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(OT) and physical conditioning. There were four 1 hr sessions of each intervention.  
**Outcome Measures:** Mean muscle strength, Muscle strength changes.

2. For those with paraplegia the range was from -0.48 (p=0.049 shoulder abductors to -0.72 (p=0.001 elbow flexors) compared to those with tetraplegia, the correlation coefficients ranged from -0.28 (p=0.345 elbow extensors) to -0.68 (p=0.010 shoulder adductors).

3. Patterns of change in muscle strength from admittance to the 15 mo follow up differed between the paraplegia group and the tetraplegia group.

Differences in strength have been observed for: elbow flexors (p=0.001) and shoulder extensors (p=0.04).

### Discussion

Five of the six 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) and Cameron et al. (1998) found that Neuromuscular stimulation (NMS) assisted exercise ergometry alone and in combination with exercise was effective for strengthening of the upper limb for SCI injured individuals well after injury.

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 and were maintained three-months post discharge for 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.

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
highlighting 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).

Bunday et al. (2014) tested the involvement of subcortical pathways while SCI subject’s
completed measures of precision grip. Authors of this study concluded that precision
grip involves premotorneuronal subcortical mechanisms and that the pathways that are
impacted after SCI are restored by long-term use of baclofen.

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, and is
correlated to a decrease in stress, pain, and depression.

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 overall muscle strength continues to improve up to 15 months’ post hospital discharge for both persons with tetraplegia and paraplegia despite large variability in patients.

There is level 5 evidence (from one observational study; Bunday et al., 2014) that the control of precision grip involves premotoneuronal subcortical mechanisms, which are lacking after SCI.

Neuromuscular stimulation-assisted exercise following a SCI is effective in improving muscle strength, preventing injury and increasing independence in all phases of rehabilitation, particularly in the first 12 months. Additionally, these positive physical outcomes are correlated to positive emotional states, such as an increase in perceived independence and a decrease in depression, anxiety, and pain.

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 Dijk 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 deficits (Flinn & Radomski 2002). In persons who are compromised by neurological sensory impairments, augmented feedback is important (Sabari 2001).
<table>
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<tr>
<th>Author Year</th>
<th>Country</th>
<th>Research Design</th>
<th>PEDro Score</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
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<tr>
<td>Popovic et al., 2006 Canada RCT PEDro=6 N=21</td>
<td><strong>Population</strong>: Age: 25-70 yr; Level of injury: tetraplegia; Severity of injury: AIS A-D, incomplete; Time Since Injury: 15-243 day; Chronicity: acute/subacute. <strong>Intervention</strong>: The control group received conventional Occupational Therapy; Intervention group received Functional Electrical Therapy and conventional Occupational Therapy. <strong>Outcome Measures</strong>: Functional Independence Measure (FIM), Spinal Cord Independence Measure (SCIM), Rehabilitation Engineering Laboratory Hand Function Test (REL Test), Consumer Perceptions.</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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<td>Kohlmeyer et al., 1996 USA RCT PEDro=10 N_initial=60; N_final=45</td>
<td><strong>Population</strong>: Mean age: 39 yr; Gender: males=40, females=5; Level of injury: C4-C6; Severity of injury: complete, incomplete. <strong>Intervention</strong>: Extremities were randomly assigned to one of four treatment groups: 1. conventional strengthening; 2. electrical stimulation; 3. biofeedback and electrical stimulation; 4. biofeedback. Participation ranged from five to six weeks post SCI. <strong>Outcome Measures</strong>: Manual muscle test, Activities of Daily Living (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.</td>
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<td>Klose et al., 1993 USA RCT PEDro=5 N_initial=31; N_final=28</td>
<td><strong>Population</strong>: Age: 18-35 yr; Gender: males=24, females=4; Level of injury: C5-C7; Time since injury: ≥1 yr. <strong>Intervention</strong>: Both groups received 45 min of aggressive exercise therapy three times per week for 12 weeks along with 30 min of neuromuscular stimulation (NMS) to assist with upper extremity muscle strength. Experimental group also received 12 wk of 30 min EMG biofeedback 3x/wk. <strong>Outcome Measures</strong>: Manual muscle test, Functional activities score.</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>
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<tr>
<td>Klose et al., 1990 USA RCT PEDro=3</td>
<td><strong>Population</strong>: Age: 18-45 yr; Level of injury: C4-C6; Severity of injury: incomplete; Time since injury: ≥1 yr.</td>
<td>1. No statistically significant differences were noted between the groups.</td>
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<td>Author Year</td>
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<tr>
<td>Foldes et al. 2015</td>
<td>USA</td>
<td>Post Test N=3</td>
<td>Intervention: All received three days/wk of therapy in two 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 wks physical therapy exercise. <strong>Outcome Measures:</strong> Manual muscle test (biceps, triceps, wrist flexors, wrist extensors), Self-care measures looking at feeding, hygiene and dressing, Mobility measure and a muscle electrical activity were also measured.</td>
<td>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 N=100</td>
<td><strong>Population:</strong> Mean Age: 28 yr; Gender: males=3, females=0; Level of Injury: C2=1, C5=2; Severity of Injury: AIS A=2, AIS B=1, Unspecified=2. <strong>Intervention:</strong> Patients with complete hand paralysis participated in a virtual hand grasping task. The virtual stop-motion hand was projected onto a screen and was controlled by the patient’s sensorimotor rhythms (SMRs). The SMRs were utilised via magnetoencephalography. Patients were asked to grasp or rest the virtual hand and were required to hold the position for a set time depending on difficulty level of the trial. Patients were also asked to attempt grasping and resting their own paralysed hand during each virtual hand trial. The intervention consisted of 200 trials (75% grasp, 25% rest) in a pseudorandom order with a 1 min break after every 20 trials. Trials were also broken down into segments of 50 trials for analysis purposes. Assessments were performed at baseline and during each trial through to post-treatment. <strong>Outcome Measures:</strong> Grasp success rate, SMR modulation, time to successful grasp.</td>
<td>1. Overall grasp success rates varied between 62 and 64% with success rate significantly better than chance for each patient (p&lt;0.001). 2. Although grasp success rates improved after breaks between trials, the success rate was not significantly different when compared to trials before breaks (p=0.22). 3. Success rates were also significantly greater than chance during grasp-only and rest-only trials (both p&lt;0.001). 4. Two patients demonstrated a significant increase in their ability to modulate their SMRs by 14.9pp and 15.0pp (both p&lt;0.05) from baseline to post-treatment. The remaining patient did not exhibit any significant improvement in modulating SMRs. 5. ANOVA analyses revealed a significant interaction between patient and session-segment (p&lt;0.001) and a significant main effect of session-segment (p&lt;0.001). 6. Patients took an average of 1.96sec to complete a successful grasp, indicating that grasping using SMRs had been learnt quickly.</td>
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</table>

- **Author Year:** The year the research was conducted.
- **Country:** The country where the research was conducted.
- **Research Design:** The method used to conduct the research.
- **Score:** The score assigned to the research design.
- **Total Sample Size:** The total number of participants in the study.
- **Intervention:** Details of the intervention used in the study.
- **Outcome:** The outcomes measured in the study.
- **Population:** Details of the population studied.
- **Methods:** The methods used in the study.
- **Outcome Measures:** The specific measures used to assess the outcomes.
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<th>Author Year Country Research Design Score Total Sample Size</th>
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<tr>
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<td>after additional biofeedback treatment 22.3% right triceps and 18.72% for left triceps, significant (p&lt;0.001).</td>
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<td>3. Correlation coefficient for manual muscle test score and EMG pretest before initial treatment was r=0.569 for right triceps and r=0.437 for left triceps, significant (p&lt;0.001).</td>
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<td>4. Increases in percentage of normal EMG before, after, and after additional treatments was significant in right and left triceps regardless of initial manual muscle test.</td>
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</table>

**Discussion**

Four of the six included studies concluded that there was no evidence for the effectiveness of augmented feedback to improve arm function in rehabilitation. These four studies are the only RCTs to date that have test augmented feedback for arm rehabilitation post SCI.

One study by Brucker et al. (1996) tested biofeedback treatment among 100 participants and found an increase in normal EMG scores in the right and left triceps, however, this sample did not include a control group. A more recent study with just three participants applied magnetoencephalography based neurofeedback and authors concluded that neurofeedback training may have the potential to be used for motor rehabilitation (Foldes et al., 2015). Given the small sample sizes within each of the six included studies, conducting additional RCTs with larger samples is necessary to gain a more conclusive understanding of the impact of augmented feedback in upper limb rehabilitation.

In a systematic review, van Dijik et al. (2005) recommended the following be considered in future research in this area:

- future studies should 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.*
There is level 2 evidence (from two randomized control trials; Klose et al., 1990; Klose et al., 1993) that the addition of biofeedback does not improve patient scores in rehabilitation more than physical exercise alone.

There is level 4 evidence (from one pre-post test; Bruker and Bulaeva, 1996) that EMG biofeedback sessions can significantly improve normal EMG muscle test scores of both triceps.

There is level 4 evidence (from one post-test; Foldes et al., 2015) that patients with complete hand paralysis can learn to significantly modulate their sensory motor rhythms using a virtual hand task over time.

Augmented feedback does not improve motor function of the upper extremity in SCI rehabilitation patients. However, biofeedback has been shown to positively effect normal EMG muscle scores in both triceps. Patients may be able to learn to regulate their sensory motor rhythms in their upper extremities using virtual tasks like hand-grasping.

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 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 baclofen 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 4 Pharmacological Interventions

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

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.

5.0 Restorative Strategies

Neuroplasticity at the site of injury post SCI can mediate functional recovery (Kakulas 2004). Motor imagery (MI) can stimulate activity-dependent neuroplasticity (Grangeon et al., 2012). Specifically, MI has been shown to stimulate cerebral reorganization and
improve motor function in patients with stroke and Parkinson’s disease (Page et al., 2009; Sun et al., 2013). Two studies authored by one group of researchers tested the use of MI in improving motor learning post SCI.

Table 5 Restorative Strategies

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<th>Author Year</th>
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<th>Research Design</th>
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<th>Total Sample Size</th>
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<tr>
<td>Di Rienzo et al. 2014b</td>
<td>France</td>
<td>Pre-Post</td>
<td>N=12</td>
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<td>Population: SCI participants (n=6); Age: 18-55 yr; Level of injury: C6/C7=6. Interventions: SCI participants received motor imagery (MI) training imbedded within traditional physiotherapy for 5 wk (3x/wk) to investigate effect of MI training on Tenodesis prehension (TP). This was compared to a healthy control group (HP) performing physical practice (PP)-based training. Outcome Measures: Magnetoencephalography (MEG) measurements, Kinesthetic and Visual Imagery Questionnaire (KVIQ), Movement Time (MT), Movement Variability (MV).</td>
<td>1. Mean KVIQ visual and kinesthetic subscores, as well as KVIQ total scores were comparable in both groups (p=0.52).</td>
</tr>
<tr>
<td>Di Rienzo et al. 2015</td>
<td>France</td>
<td>Pre-Post</td>
<td>N=8</td>
<td></td>
<td>Population: SCI participants (n=4); Mean age: 27.5 yr; Gender: males=2, females=2; Severity of Injury: AIS C6=4; Mean time since injury: 14.5 mo. Interventions: SCI participants had motor imagery (MI) training imbedded within traditional physiotherapy for 5 additional wk (3x/wk) to investigate effect of MI training on Tenodesis prehension (TP), compared to healthy control group (HC) performing physical practice (PP)-based training. Outcome Measures: Magnetoencephalography (MEG) measurements, Motor performance data, Kinesthetic and Visual Imagery Questionnaire (KVIQ), Movement Time (MT), Movement Variability (MV), Synthetic aperture magnetometry (SAM).</td>
<td>1. No statistically significant differences between groups on KVIQ scores or sub-scores (all p&gt;0.05).</td>
</tr>
</tbody>
</table>
Discussion

Di Rienzo et al. (2014b, 2015) conducted two small studies and applied the same methodology involving SCI participants receiving MI and traditional physiotherapy compared to healthy controls performing physical practice. These studies resulted in mixed findings, however, SCI participants' movement time and variability generally improved after MI.

Conclusion

There is level 4 evidence (from two pre-post studies; Di Rienzo et al., 2014b, 2015) that MI treatment incorporated into physiotherapy for individuals with SCI may help to improve prehensile tenodesis performance.

Motor imagery may be an effective intervention for improving prehensile tenodesis performance in persons with SCI.

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 SCI, 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 depend on the 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 closely resembles 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 rhythmical 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 scarce 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).

Seven studies were found that tested the use of MP, SS, transcranial direct current stimulation (tDCS), transcutaneous electrical nerve stimulation (TENS), vibration therapy, and repetitive transcranial magnetic stimulation (rTMS) in changing the cortex.

Table 6 Plasticity of Motor Systems

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<thead>
<tr>
<th>Author Year</th>
<th>Country</th>
<th>Research Design</th>
<th>PEDro Score</th>
<th>N Initial</th>
<th>N Final</th>
<th>Population</th>
<th>Methods</th>
<th>Outcome</th>
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<tbody>
<tr>
<td>Beekhuizen &amp; Field-Fote 2008</td>
<td>USA</td>
<td>RCT</td>
<td>5</td>
<td>24</td>
<td>18</td>
<td>Mean age: 38 yr; Gender: males=22, females=2; Level of injury: tetraplegia; Severity of injury: AIS C=11, D=13; Mean time since injury: 67 mo; Chronicity=chronic.</td>
<td>Interventions: One of four conditions two hr per day, 5 days/wk: 1) Massed practice training (MP); 2) Somatosensory peripheral nerve stimulation (SS); 3) MP + SS combined; 4) No intervention (control).</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). 2. MP+SS and SS groups significantly improved motor function scores when compared to the control group (p&lt;0.001, p&lt;0.05, respectively). MP+SS improved more than MP and SS alone (p&lt;0.01). 3. MP+SS and SS groups also significantly improved pinch grip forces (p&lt;0.01). MP+SS was the only group to have a significant sensory function improvement (p=0.01).</td>
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| Beekhuizen & Field-Fote 2005 | USA     | RCT             | 8           | 10        |         | 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 mo. | Interventions: Subjects participated in two hours of massed practice (MP) therapy five times per week for three weeks or MP+median nerve somatosensory stimulation (SS). Massed practice (MP) | 1. Pinch grip scores: differences were noted in the MP+SS group (Z=-2.023, p<0.05) only. 2. The MP+SS group also showed greater increase in pinch grip strength than the MP group (U=2.0, p<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,
training focused on continuous repetitions of the following: gross upper extremity movement, grip, and grip with rotation. Tasks in each block were performed for 25 min before moving to the next category.

**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, Motor evoked potentials amplitude.

p<0.05). No statistical differences were noted for the MP group.
4. Timed test scores between the two groups were also found to be statistically different (U=1.0, p<0.05).
5. Jebsen test scores: pre-and post-test scores were different for the MP+SS group (Z=−2.023, p<0.05). The MP+SS group showed greater improvement than the MP group (U=3.0, p<0.05).
Cortical Excitability: No significant differences were noted between the two groups.

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**Population:** Mean Age: 43.7 yr; Gender: males=21, females=3; Injury etiology: Motor Vehicle Accident=17, Diving=2. Non-traumatic=1, Unspecified=4; Severity of Injury: AIS C=9, AIS D=11, Unspecified=4; Level of Injury: C4=1, C5=4, C6=10, C7=5.

**Intervention:** Patients received three types of stimulation in a randomized order: transcranial direct current stimulation (tDCS), transcutaneous electrical nerve stimulation (TENS), and vibration therapy. Both TNS and vibration therapy was performed on the volar aspect of the wrist. tDCS was performed on the primary left/right motor area and on the contralateral supraorbital area. During each condition, the patients engaged in functional task practice. The intervention was provided once for each condition with a 1 wk break between each. Assessments were conducted at baseline, post-treatment and at 30 min post treatment.

**Outcome Measures:** Nine-hole Peg Test (9HPT), pinch strength, Corticomotor excitability/motor-evoked potentials, Visuomotor tracking task.

1. Results on the 9HPT improved significantly from baseline to post treatment after patients received TENS (p=0.003) and tDCS (p=0.05) with improvements maintained from baseline to 30 min post treatment (p<0.001 and p=0.003 respectively).
2. Vibration therapy did not significantly change from baseline to post treatment or 30 min post treatment.
3. Pinch strength significantly improved from baseline to post treatment after vibration therapy only (p=0.03). At 30 min post treatment, patients demonstrated improved pinch strength after both vibration therapy (p=0.03) and tDCS (p=0.005) compared to baseline.
4. Visuomotor tracking did not improve from baseline to post treatment for any of the conditions. Only tDCS improved from baseline to 30 min post treatment (p=0.05).
5. Corticomotor excitability improved significantly from baseline to post treatment after TENS (p=0.003) only but at 30 min post treatment, only vibration therapy demonstrated a significant improvement compared to baseline (p=0.006).

**Effect Sizes:** Forest plot of standardized mean differences (SMD±95%C.I.) as calculated from pre- and post-intervention data.
Population: SCI Group (n=11): Mean Age: 46.7 yr; Gender: males=10, females=1; Severity of Injury: AIS C=5, AIS D=6.
Healthy Group (n=10): Mean Age: 33.7 yr; Gender: males=6, females=4.

Intervention: Patients and healthy volunteers were randomized to receive repetitive transcranial magnetic stimulation (rTMS) or sham-rTMS to the corticomotor region that controlled the weaker hand (trained hand). After 1 wk of treatment, the two groups were crossed over for an additional week. Both groups were asked to complete the Nine-hole Peg Test (9HPT) during each rTMS/sham-rTMS session and on days in between. The patients completed three sessions of each condition. Assessments were completed at baseline and at post treatment for each condition.

Outcome Measures: Jebsen-Taylor Hand Function Test (JTT), pinch strength, grasp strength, Nine-hole Peg Test (9HPT), motor threshold (MT).

Effect Sizes: Forest plot of standardized mean differences (SMD±95%C.I.) as calculated from pre- and post-intervention data.

1. Improvements in JTT scores revealed large effect sizes for the rTMS condition (0.85) while the sham-rTMS condition yielded a smaller effect size (0.42). Although both conditions demonstrated an improvement in time to complete the JTT but no significant differences were reported (p=0.4).
2. Differences between the trained hand and non-trained hand approached statistical significance in time to complete the JTT (p=0.06).
3. No significant differences were found for grasp strength and pinch strength between the two conditions from baseline to post treatment although the rTMS condition produced a larger effect size in grasp strength on the trained hand (0.67) compared to the sham-rTMS condition (0.39).
4. Performance on the 9HPT improved significantly, regardless of condition, for the SCI group and the healthy group during the first six days of treatment (p<0.0006 and p=0.05 respectively).
5. Resting and active MT did not differ significantly between rTMS and sham-rTMS for both the SCI group and the healthy group at post treatment.

Gomes-Osman & Field-Fote 2014
USA
RCT
PEDro=6
N=21
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<th>Author Year</th>
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<th>Outcome</th>
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<td>RCT</td>
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**Population:** Experimental Group (n=11):
Mean Age: N/R; Gender: males=7, females=4; Level of Injury: C3=2, C4=3, C5=1, C6=3, C7=2; Severity of Injury: AIS B=1, AIS C=4, AIS D=6.

Control Group (n=13): Mean Age: N/R; Gender: males=10, females=3; Level of Injury: C4=2, C5=2, C6=5, C7=4; Severity of Injury: AIS A=2, AIS B=3, AIS C=5, AIS D=3.

**Intervention:** Patients were randomly assigned to either an experimental group or a control group then further divided into four conditions, Unimanual Somatosensory Stimulation (Uni-SS), Bimanual SS (Bi-SS), Unimanual Functional Electrical Stimulation (Uni-FES) and Bimanual FES (Bi-FES). For patients who received SS, electrodes were placed over median nerve in the wrist. FES electrodes were also placed on the median nerve in the wrist but FES was only triggered when muscle activation exceeded the threshold value. During each session, patients completed a set of activities (either unimanually or bimanually) including grasping, grasping and rotation, pinching, pinch with rotation, and finger isolation. Control patients received the interventions after an initial delayed control period. The interventions were provided 2hr/day, 5day/wk for a total of 3 wk. Assessments were conducted at baseline and at post treatment.

**Outcome Measures:** Jebsen Taylor Hand Function Test (JTHF), Corticomotor activity, Chedoke Arm and Hand Activity Inventory (CAHAI).

**Effect Sizes:** Forest plot of standardized mean differences (SMD±95%C.I.) as calculated from pre- and post-intervention data.

1. A significant Time x Group interaction was reported for JTHF scores with the experimental group improving significantly from baseline to post treatment on the JTHF compared to the control group (p=0.03).
2. A significant improvement in JTHF scores were found after the control group received the interventions (p=0.01) when comparing baseline to post treatment. However, the correlation between initial scores and the amount of change was not significant (p=0.19) indicating the improvement may have been due to chance.
3. After analysing all four conditions, only a significant effect of Time was found (p=0.0006) indicating that regardless of intervention, patients all demonstrated improvement on JTHF scores from baseline to post treatment.
4. No significant difference in JTHF scores were found between FES and SS from baseline to post treatment (p=0.46).
5. No significant difference in JTHF scores were found between bimanual and unimanual activities from baseline to post treatment (p=0.57).
6. A significant Time x Group interaction was reported for Corticomotor activity with the experimental group demonstrating an increase in Corticomotor map area whilst the control group did not demonstrate any changes (p=0.03).
7. A significantly greater amount of change from baseline to post treatment was found for patients in both bimanual conditions on the CAHAI compared to patients in the unimanual conditions (p=0.03).
<table>
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<tr>
<th>Author Year Country</th>
<th>Research Design Score</th>
<th>Total Sample Size</th>
<th>Methods</th>
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<td>Hoffmann et al. 2013; FES+SS vs. Delayed Intervention (Control)</td>
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- JTHFT
- CAHA!
- Pinch
- SWMT
- HAQ

Favours Control Standardized Mean Difference (95%CI) Favours Treatment

Hoffmann et al. 2013; Bimanual vs. Unimanual

- JTHFT
- CAHA!
- Pinch
- SWMT
- HAQ

Favours Control Standardized Mean Difference (95%CI) Favours Treatment

Hoffmann et al. 2013; FES vs. SS

- JTHFT
- CAHA!
- Pinch
- SWMT
- HAQ

Favours Control Standardized Mean Difference (95%CI) Favours Treatment

**Population:** Tetraplegic group (n=16): Mean age: 45.9±14.5 yr; Gender: males=10, females=6; Mean Spinal Cord Independence Measure-III (SCIM-3): 33.4±16.8; Level of injury: AIS A=8, AIS B=8; Severity of Injury: C4-C6; Mean time since injury: 13.3±10.9 yr. Paraplegic group (n=16): Mean age: 50.0±13.2 yr; Gender: males=12, females=4; Level of injury: AIS A=14, AIS B=2; Severity of Injury: T1-L4; Mean time since injury: 18.5±12.4 yr. Healthy controls (n=16): Mean age: 43.1±16.9 yr; Gender: males=8, females=8.

**Intervention:** Induction of the Rubber Hand Illusion (RHI) through synchronous multisensory visuo-tactile bodily stimulation (cheek and rubber hand vertically aligned with real hand) to determine the correlation with plastic remapping.

**Outcome Measures:** 6-item questionnaire; Illusion Related Questions (IRQ), Illusion

1. Three-way interaction between number of drifts, group and stimulation-type and body part was significant (p=0.02).
2. Tetraplegic group showed significantly greater values in IRQ than ICQ responses in hand-synchronous (p=0.0001), hand-asynchronous (p=0.026), and face-synchronous conditions (p=0.024).
3. In paraplegic group significant values found in IRQ over ICQ responses in hand-synchronous (p<0.0001) and hand-asynchronous (p=0.0002); whereas in healthy group only found significance in hand-synchronous condition (p<0.0001).
4. No statistically significant correlations were found between drifts or questionnaire responses and the TAS, the BFI-10, the SCIM-3 and the NLI.
Control Questions (ICQ), Big-Five Inventory (BFI-10), Tellegen Absorption Scale (TAS).

**Population: Unimanual group (n=6):** Mean age: 42 yr; Gender: males=5, females=1; Level of Injury: C5=1, C3=1, C4=4; Severity of Injury: B=1, C=4, D=1.  
**Bimanual group (n=7):** Mean age: 34.7 yr; Gender: males=5, females=2; Level of Injury: C5=3, C6=4; Severity of Injury: AIS B=3, AIS C=4.  
**Intervention:** Participants were randomly assigned to receive either unimanual or bimanual massed practice in conjunction with SS for 2 hours a day for 5 days a week, over a three-week period.  
**Outcome Measures:** Jebsen Taylor Hand Function Test duration (JT HF T), Chedoke McMaster Hand Activity Inventory (CAHAI), Semmes-Weinstein Monofilament Test (SWMT), Pinch-grip strength (lbs), Corticomotor map area, Resting corticomotor threshold.

1. JTHFT scores improved significantly for both groups (p=0.01), and both groups completed tasks in a shorter period of time. There were no significant differences on this test between groups.  
2. CAHAI scores were significantly negatively correlated with JTHFT scores (p=0.02) indicating that increased scores on the CAHAI were correlated to faster completion times of the JTHFT. CAHAI scores improved significantly for both groups (p=0.02), but there were no significant differences between groups.  
3. SWMT scores improved significantly for both groups (p=0.04), there were no significant differences between groups over time.  
4. There were no significant changes in pinch grip between groups, or over time.  
5. Post-intervention there was a mean increase in cortical map area (p=0.05), indicating a trend towards enlargement of cortical map. There were no significant changes in cortical map area between groups.  
6. There were no significant differences between groups or overtime in resting corticomotor threshold.  

**Effect Sizes:** Forest plot of standardized mean differences (SMD±95%CI) as calculated from pre- and post-intervention data.

- **JTHFT**  
  - 0.40 (0.90,1.60)  
- **CAHAI**  
  - 0.08 (-1.13,1.26)  
- **SWMT**  
  - 0.00 (-1.39,1.19)  
- **Pinch grip strength**  
  - 0.21 (-0.98,1.40)  
- **Corticomotor map area**  
  - 0.04 (-1.15,1.21)  
- **Resting corticomotor threshold**  
  - 0.61 (-0.63,1.82)

**Population: Group 1 (n=10):** Mean Age: 33.2±6.1 yr; Gender: males=8, females=2; Handedness: Rt=9, Lt=1; Level of Injury: C5=5, C6=4, C7=1; Severity of Injury: AIS C=4, AIS D=6; Mean time since injury: 21.8±19.1 yr.  
**Group 2 (n=10):** Mean Age: 38.7±12.1 yr; Gender: males=8, females=2; Handedness: Rt=8, Lt=2; Level of injury: C5=5, C6=4, C7=1; Severity of Injury: AIS C=4, AIS D=6; Mean time since injury: 21.8±19.1 yr.

1. There was no statistically significant difference between the 3 groups in age, sex, duration of illness, ASIA scale, handedness and level of injury (p>0.05).  
2. There was a highly significant increase in post-treatment ASIA motor score in group I and group II (p<0.001) but not group III (p=0.05).  
3. Comparison between pre and post-treatment scores in light touch and pinprick values showed a significant increase in both post -treatment in
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<td>UK</td>
<td>Pre-post</td>
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Population: Age: 41-54 yr; Gender: males=3, females=1; Level of injury: C5=4; Severity of injury: AIS D=4; Time since injury: 1.25-8 yr.

Intervention: Five days of sham repetitive transcranial magnetic stimulation (rTMS) followed by five days of therapeutic stimulation (rTMS).

Outcome Measures: ASIA Impairment Scale (AIS), Nine Hole Peg Board.

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. These findings were supported in a more recent study (Nasser et al., 2014), however, Nasser et al (2014) also found that the combination of MP and SS resulted in a greater improvement than MP alone (Nasser et al., 2014). The mechanism of how SS and FES improves hand functioning has also been studied (Hoffman & Field-Fote, 2013). In unimanual and bimanual SS and FES conditions only a significant effect of time was found, regardless of intervention, with each condition resulting in improvements of hand functioning.
Multisensory visuo-tactile bodily stimulation has also been tested and illusory ownership over the hand was found to be more likely to occur in the presence of upper spinal levels (Scandola et al., 2014). 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. A more recent RCT found that rTMS resulted in improvements in hand functioning but not grasp strength or motor threshold (Gomes-Osman & Field-Fote, 2014).

One study tested the use of transcutaneous electrical nerve stimulation (TENS), transcranial direct current stimulation (tDCS), and vibration therapy (Gomes-Osman & Field-Fote, 2015). Authors concluded that TENS, tDCS, and vibration therapy resulted in significant improvements in hand functioning when combined with functional task practice.

For restorative strategies to be feasible for use in everyday clinical practice it is important that the interventions be available in the clinic and at home (Beekhuizen & Field-Fote 2005).

**Conclusion**

*There is level 1a evidence (from three randomized controlled trials; Bekkhuizen & Field-Fote 2005, 2008; Hoffman & Field-Fote 2013) 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 1b evidence (from one randomized control trial; Gomes-Osman & Field-Fote, 2014) that showed that rTMs treatment in individuals with chronic stable SCI may produce reductions in corticospinal inhibition that resulted in clinical and functional changes for several weeks after treatment.*

*There is level 2 evidence (from two randomized controlled trials; Gomes-Osman & Field-Fote, 2015; Hoffman and Field-fote, 2010) that showed that tDCS, TENS, vibration therapy and repetitive massed practice resulted in significant improvements in upper extremity function and pinch strength.*

*There is level 4 evidence (from one post-test study; Scandola et al., 2014) that showed that the induction of the rubber hand illusion through synchronous multisensory visuo-tactile bodily stimulation resulted in ownership of the hand.*
There is level 4 evidence (from one pre-post study; Belci et al., 2004) that showed therapeutic TMS can lower intracortical inhibition, which is linked to better clinical motor scores.

There is level 4 evidence (from one pre-post study; Nasser et al., 2014) that showed massed practice and somatosensory stimulation significantly improved motor function and pinch grip strength compared to traditional rehabilitation programs over time.

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. Repetitive activity combined with somatosensory stimulation can significantly increase the functionality of upper extremities, potentially improving the overall quality of life for patients. 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 SCI patients with paraplegia (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 assists in minimizing of posttraumatic cord shrinkage and sparing of the ventral horn neurons (Politis & Korchinski 1990; Ran et al., 1992; Tsay 1974; Wu 1990).
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<tr>
<th>Author Year Country Research Design Score Total Sample Size</th>
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<th>Outcome</th>
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<td><strong>Population:</strong> Age: 28-69 yr; Gender: males=18, females=6; Time since injury: 5-33 yr; Length of shoulder pain: 4 mo -22 yr. <strong>Intervention:</strong> Subjects received either acupuncture treatments (sessions lasted 20-30 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). <strong>Outcome Measures:</strong> Intake questionnaire (demographics and medical history), Weekly log, Wheelchair users shoulder pain index (WUSPI), Numeric rating scale (NRS), Verbal rating scale (VRS), Range of Motion (ROM).</td>
<td>1. There was a significant effect of time for both treatments on performance corrected (PC)-WUSPI (Acupuncture p&lt;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&lt;0.05) 3. There was a significant effect of time for both acupuncture and Trager groups for average pain &amp; most severe pain (p&lt;0.01, p&lt;0.001 respectively), for the least severe pain the acupuncture group showed a significant reduction (p&lt;0.01) compared to the Trager group. 4. Verbal response scores- there was a statistically significant treatment effect for both groups (p=0.001).</td>
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<tr>
<td><strong>Effect Sizes:</strong> Forest plot of standardized mean differences (SMD±95%C.I.) as calculated from pre- and post-intervention data.</td>
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<td>Dyson-Hudson et al. 2001; Trager Psychophysical Integration</td>
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<td></td>
<td>PC-WUSPI: 0.51±0.43,1.45</td>
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<td></td>
<td>ROM - internal rotation at 90° (IR90): 0.36±0.57,1.29</td>
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| **Wong et al., 2003 Taiwan RCT PEDro=5 N=100** |         |         |
| **Population:** Mean age: 35 yr; Gender: males=80, females=20; Level of injury: paraplegia=63, tetraplegia=37; Severity of injury: AIS A-B; Chronicity: acute. **Intervention:** 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 min, 5x/wk. **Outcome Measures:** ASIA Impairment Scale (AIS) (sensory + motor), Functional Independence Measure (FIM). | 1. Acupuncture group - sensory, motor + FIM scores improved significantly day of D/C + one yr after injury (p<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 + one yr post significant improvement AIS + FIM in acupuncture versus control p<0.05. 3. More patients in acupuncture group improved to AIS grade B + C or better at D/C + one-yr post p<0.05. |         |
| **Effect Sizes:** Forest plot of standardized mean differences (SMD±95%C.I.) as calculated from pre- and post-intervention data. |         |         |
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 RCT 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. This study demonstrated significant improvements in the acupuncture group on the day of discharge from hospital and one year after injury. The control group (auricular acupuncture) had significant improvement in only one outcome one-year post-injury follow up. The acupuncture group revealed significant improvement in all AIS and FIM scores when compared to the control group. An inherent bias may have been present 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 patients with tetraplegia 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 8 Splinting of the Hand

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<thead>
<tr>
<th>Author Year</th>
<th>Country</th>
<th>Research Design</th>
<th>Score</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
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<tbody>
<tr>
<td>Harvey et al., 2006</td>
<td>Australia</td>
<td>RCT</td>
<td>PEDro=8</td>
<td>N_initial=44; N_final=43</td>
<td>Population: Age: N/R; Gender: N/R; Injury etiology: SCI=23, Stroke=14, ABI=7; Mean time since injury: 4 yr. Intervention: Experimental group: thumbs splinted into a stretched, abducted position, every night (average eight hours), for 12 wk. 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.</td>
<td>1. After 12 wk, 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. Twenty-two 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 after treatment, was 0.87.</td>
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<td>Author Year</td>
<td>Country</td>
<td>Research Design</td>
<td>Score</td>
<td>Total Sample Size</td>
<td>Methods</td>
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<tr>
<td>DiPasquale-Lehnerz 1994</td>
<td>USA</td>
<td>RCT</td>
<td>PEDro=4</td>
<td>N_{initial}=13; N_{final}=9</td>
<td>Population: Age: 18-42 yr; Gender: males=12, females=1; Time since injury: 6–8 wk.</td>
<td>1. No significant differences were noted between the two groups—all subjects demonstrated improvement in hand function and pinch strength.</td>
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<td>Intervention: Experimental group was given long or short orthosis to be worn at night (eight hours) as soon as the subject could tolerate it.</td>
<td>2. At eight wks 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).</td>
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<td>Outcome Measure: Pinch strength, Functional activity use, Jebsen-Taylor Hand Function (JTHF).</td>
<td>3. At the 12-wk marker, improvement could be seen on the card subtest (p&lt;0.05).</td>
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<td>4. An increase in pinch strength was noted at eight wks for all subjects (p&lt;0.05) and at 12 wk nine remaining subjects (p&lt;0.05).</td>
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<td>Effect Sizes: Forest plot of standardized mean differences (SMD±95%CI.) as calculated from pre- and post-intervention data.</td>
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Discussion

Even though splinting and orthotic fabrication is an accepted practice, there is minimal research 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 is 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 Stieger’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 SCI patients.

Harvey et al. (2006) noted that twelve weeks of nightly stretch does not reduce thumb web-space contractures in people with a neurological condition (stroke, acquired brain injury, 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 is 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 orthosis 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 (e.g., turning cards, and picking up small objects) for those wearing the splint.

There are several published surveys that address 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). Research using larger study sizes, objective measures, and studying the type of neurological condition being splinted is needed to determine the effectiveness 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).*
6.0 Subacute Phase of Rehabilitation

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. The structures of the upper limb are therefore 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) found that individuals with SCI reported that their dependence in personal care assistance 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,” to address upper limb problems. Recent studies have also started to explore factors that relate to upper extremity pain (Barbetta et al., 2016).

In the subacute phase of rehabilitation, the strategies that were initiated during the acute phase of rehabilitation are continued (Field-Fote, 2009). Adjustments may be made to the approaches to rehabilitation, however, working towards the therapeutic goals to help persons with SCI achieve optimal functioning continues. Exercises to strengthen the upper limb during this phase of rehabilitation can include progressive increases to the resistance of weight to improve muscle strength (Field-Fote, 2009). Hand grasping and opening are also a focus of this phase of rehabilitation.
### Table 9 Subacute Phase of Rehabilitation

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<tr>
<th>Author Year</th>
<th>Country</th>
<th>Research Design</th>
<th>Score</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
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<tbody>
<tr>
<td>Stahl et al. 2015</td>
<td>USA</td>
<td>Post-Test</td>
<td>N=16</td>
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<td>Population: SCI population (n=8): Mean age: 37±4.4 yr; Gender: males=7, females=1; Level of injury: AIS C4-C7=1, AIS C5=1, AIS C5-C7=6; Mean time since injury: 10.9 yr. Healthy controls (n=8): Mean age: 26.6±2.4 yr; Gender: males=6, females=2. Intervention: Measured hand kinematics and surface electromyography from seven muscles of the hand and wrist during attempts at maximum hand opening as well as reaching for four balls of different diameters. Outcome Measures: Hand kinematics, Surface electromyography (EMG) of wrist and hand muscles. Peak aperture, Box-and-Blocks Test (BBT), Jebsen-Taylor Hand Function (JTHF).</td>
<td>1. Maximum hand opening was reduced in SCI participants as compared to controls (p=0.002). 2. No correlation between maximum voluntary hand opening and hand function with BBT (p=0.934) and JTHF (p=0.701). 3. SCI participants had greater EMG activity in AD (anterior deltoid) (p=0.018), TRI (triceps brachii) (p=0.009), FCU (flexor carpi ulnaris) (p=0.020), and FDS (flexor digitorum superficialis) (p=0.051) as compared to AB group. 4. Co-activation ratios at wrist and hand were reduced for the SCI group compared to the control group (wrist: p=0.030, hand: p=0.006). 5. Peak aperture for balls B, C, and D was larger in the AB group than the SCI group (all p≤0.042), while peak aperture for the smallest ball A was not different (p=0.163). 6. AB participants utilized less of their aperture range compared to the SCI group (p=0.035). 7. There was no difference in number of muscle coordination patterns (p=0.227) as both groups required three patterns to sufficiently account for &gt;90% of EMG data variance. 8. For the SCI group, the wrist flexion muscle coordination pattern (p=0.002) increased activation as the ball size increased. 9. The wrist extension muscle coordination pattern also showed a nonsignificant trend to increase activation as ball size increased (p&gt;0.05).</td>
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Discussion

Opening the hand to grasp for objects is often compromised after cervical SCI. Stahl et al. (2015) hypothesized that persons with SCI demonstrate neuromuscular coordination strategies, allowing object-specific hand aperture scaling while reaching. This was tested with different sized objects and authors concluded that motor planning for aperture modulation is preserved despite the limitations on hand opening capacity and muscle co-activity (Stahl et al., 2015).

The increased use of the upper extremity has been associated with a higher occurrence of musculoskeletal pain among SCI injured individuals (Boninger et al., 2005). A retrospective chart review considered factors that are associated with musculoskeletal pain. This study found that women, tetraplegia, being over 41 years of age, exclusively

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<th>Author Year</th>
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<tbody>
<tr>
<td>Barbetta et al. 2016</td>
<td>Brazil</td>
<td>Case Series</td>
<td>N=564</td>
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<tr>
<th>Methods</th>
<th>Outcome</th>
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<tr>
<td>Population: Mean age: 34.0 yr; Gender: males=446, females=118; Mean BMI: 22.4±4.8 kgm²; Level of injury: C1-5=32, C6-1=189, T2-6=146, T7-S5=197; Severity of injury: AIS A=317, AIS B=85, AIS C=48, AIS D=54; Mean time since injury: 5.0 yr.</td>
<td>1. Prevalence of musculoskeletal UE pain was 27.7% (CI 95%, 24.0–31.4).</td>
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<td>Intervention: No intervention. Retrospective charts were reviewed to analyze impact of demographic (gender, age, body mass index (BMI)) and injury based variables (level of injury, severity of injury, time of injury, type of mobility, locomotion aid) on occurrence of musculoskeletal pain.</td>
<td>2. In groups with and without pain, age (p=0.185), BMI (p=0.312) and mobility aid (p=0.101) showed no statistically significant difference.</td>
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<td>Outcome Measures: Musculoskeletal pain.</td>
<td>3. Gender (p=0.007), time of injury (p&lt;0.001), level (p&lt;0.001) and completeness of injury (p=0.039), and locomotion (p&lt;0.001) were significantly different between pain and no pain groups.</td>
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<td>4. Women are twice as likely to experience UE pain as men (95% CI, 1.3-3.4).</td>
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<td>5. Individuals aged ≥41 yr are twice as likely to have pain as are patients &lt;24.7 yr of age (95% CI, 0.3-0.9).</td>
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<td>6. Individuals with injury that has lasted &lt;1 yr have a greater risk of pain than individuals in other quartiles; the former are two times more likely to experience UE pain than are individuals with 1.1–2.8 yr of injury (95% CI, 0.2-0.7) and three times more likely than individuals with 2.9–6.8 (95% CI, 0.2-0.5) and 6.9+yr of injury (95% CI, 0.2-0.6).</td>
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<td>7. The individuals exclusively using wheelchairs for locomotion had twice the risk of pain than did those in the ‘wheelchair+orthostatism’ (95% CI, 0.3-0.8) and ‘wheelchair+walking exercise’ groups (95% CI, 0.3-1.0).</td>
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<td>8. There was no difference in a comparison with the ambulators.</td>
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using a wheelchair for locomotion, and being less than one-year post-injury were significantly related to the presence of musculoskeletal pain (Barbetta et al., 2016).

The following are the identified risk factors for the development of musculoskeletal pain (Barbetta et al. 2016):

- Gender - women.
- Completeness of injury - tetraplegia.
- Time of injury - persons less than one-year post-injury.
- Age – being over 41 years of age.
- Locomotion – exclusively using a wheelchair.

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). Cognitive-behavioural strategies have also been suggested to be beneficial among SCI injured individuals (Heutink et al., 2013).

As identified in the Consortium for Spinal Cord Medicine (2005) document, modification of task performance based on ergonomic analysis has been shown 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. 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 a series of recommendations regarding the upper limb. First, 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. Additionally, patients should have their function, ergonomics, equipment and level of pain assessed at each periodic review. At this time other potential risk factors can also be addressed, such as changes in medical status, new medical problems, and changes in weight. Lastly, general housekeeping measures which can benefit the patient were identified as reducing the number of non-level transfers per day, assessing work related activities and re-evaluating their current exercise program.
The Consortium for Spinal Cord Medicine (2005), Sipski and Richards (2006), Campbell and Koris (1996), Dalyan et al. (1999), and Nichols et al. (1979), identified the following as important areas of further research in the upper limb:

- Research to validate and support the adoption of a standardized classification scheme with accompanying diagnostic procedures and criteria.
- Determine the best methods to treat existing painful shoulder lesions and prevent others so that these individuals are as pain free and independent as possible.
- Further study is needed to elucidate the mechanisms of pain in this group and to establish why some patients who have pain early in rehabilitation continue to have pain at discharge and others do not.
- Multicentre RCT of intervention are also needed to reduce the severity and impact of different subtypes of SCI pain.
- Possible links between pain during rehabilitation and pain in long-term SCI.
- Detailed investigation of the biomechanics of activities commonly performed by people with tetraplegia to enhance understanding of the stresses placed on the shoulder and the mechanical causes of shoulder pain.
- Causes of shoulder pain in the acutely injured individual compared to the chronic spinal cord injured person.
- Implementation of upper limb pain prevention and management programs for persons with SCI- acute and ongoing patient education about basic biomechanical principles on avoiding impingement and overuse.
- Managing the early signs of strain and overuse and knowledge of several alternative techniques of ADL.
- Education and training in endurance and balanced strengthening of muscles acting around the shoulder and optimizing posture to achieve a normal alignment of shoulder, head, and the spine are critical for avoidance of injuries.
- Ergonomically designed environmental changes and wheelchair, home and work modifications.
- Further clinical and biomechanical research to improve the preventative measures and treatment methods of upper limb pain in SCI persons in order for them to maintain optimal functional status.

Conclusion

There is level 4 evidence (from one post-test study; Stahl et al., 2015) that among persons with chronic SCI motor planning for aperture modulation is preserved.

There is level 4 evidence (from one case series; Barbetta et al., 2016) that the presence of musculoskeletal pain is not necessarily related to lifestyle factors (such as BMI and mobility aid) but more of a function of other demographic factors (such as gender, age, and level of injury).
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. The incidence of shoulder pain in acute tetraplegia (less than six months post injury) has been reported to range from 51%-78% (Salisbury et al., 2003). In the acute phase after SCI, shoulder pain is reported in approximately 75% of patients (Silfverskiold & Waters 1991; Wanring & Maynard 1991), and 33%-63% of patients in the chronic phase (greater than 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. Subbardo et al. (1994) and Sie et al. (1992) reported that shoulder pain is still prevalent in individuals 15-20 years’ post injury. Pain experienced above the injury level during the first three to six months after injury is different than the pain experienced one 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 & Twomey 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), this results in difficulty determining whether shoulder pain is a function of duration of SCI or simply a part of the normal aging process (Neer & Welsh 1977).

The range in prevalence of shoulder pain is 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 make it difficult to assess the true prevalence of shoulder pain in individuals with shoulder pain (Pentland & Twomey 1991).

 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.
### Table 10 Shoulder Injury Intervention

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<th>Author Year</th>
<th>Country</th>
<th>Research Design</th>
<th>PEDro Score</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
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</table>
| Hicks et al., 2003 | Canada | RCT | PEDro=5 | N=32; Nfinal=24 | Population: Age: 19-65 yr; Level of injury: C4-L1; Severity of injury: AIS A-D; Time since injury: 1-24 yr. 
**Intervention:** Experimental group participated in a progressive exercise training 2x/wk for nine mo-each session offered on alternative days lasting 90-120 min. 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, Quality of Life (QOL). |
| 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 group 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). | Effect Sizes: Forest plot of standardized mean differences (SMD±95%C.I.) as calculated from pre- and post-intervention data. |

| Dyson-Hudson et al., 2001 | USA | RCT | PEDro=7 | N=21 | Population: Age: 28-69 yr; Gender: males=18, females=6; Time since injury: 5-33 yr; Length of shoulder pain: 4 mo-22 yr. 
**Intervention:** Subjects received either acupuncture treatments (sessions lasted 20-30 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:** Weekly log, Wheelchair users shoulder pain index (WUSPI), Numeric rating scale (NRS), 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. |
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<th>Author Year</th>
<th>Methods</th>
<th>Outcome</th>
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<tr>
<td>Curtis et al., 1999</td>
<td>Both groups completed the Wheelchair Users Shoulder Pain Index (WUSPI) every two mo for six mo. The experimental group attended a 60 min educational session where they were instructed in five shoulder exercises.</td>
<td>4. Verbal response scores—there was a statistically significant treatment effect for both groups (p=0.001).</td>
</tr>
<tr>
<td>Population: Mean age: 35 yr; Gender: males=35, females=7; Level of injury: cervical-lumbar; Mean duration of wheelchair use: 24 yr.</td>
<td>Outcome Measures: Wheelchair User's Shoulder Pain Index (WUSPI), Visual Analog Scale (VAS).</td>
<td>Effect Sizes: Forest plot of standardized mean differences (SMD±95%C.I.) as calculated from pre- and post-intervention data.</td>
</tr>
<tr>
<td>Interventions: Both groups completed the Wheelchair Users Shoulder Pain Index (WUSPI) every two mo for six mo. The experimental group attended a 60 min educational session where they were instructed in five shoulder exercises.</td>
<td>1. There were no significant differences between control and experimental group in age, yr of wheelchair use or activity levels.</td>
<td>0.51 (-0.43, 1.45)</td>
</tr>
<tr>
<td>2. When looking at the effect of exercise of intervention on performance corrected (PC) WUSPI, a two factor repeated measures ANOVA showed a significant effect of time only (p=0.048).</td>
<td>0.36 (-0.57, 1.29)</td>
<td></td>
</tr>
</tbody>
</table>

Discussion

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 RCT found that supervised exercise produced results similar to arthroscopic surgery for patients with impingement syndrome (Brox et al., 1993), however; this study did not include SCI patients.
Exercise has been shown to reduce pain in a RCT 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). RCT’s incorporating stretching into an exercise program for individuals who use manual wheelchairs found stretching exercises were associated with decreased reported shoulder pain intensity (Curtis et al., 1999; Hick et al., 2003).

One RCT 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).

The following are the many identified risk factors for the development of injury and pain in the shoulder:

- 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).

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.

6.2 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 that pain localized in the elbow region in persons with tetraplegia and paraplegia was present in approximately 15% of SCI injured individuals, while a study by Dalyan et al. (1999) found that up to 35% of participants in their study 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 11 Elbow, Wrist and Hand Injuries

<table>
<thead>
<tr>
<th>Author Year Country</th>
<th>Methods</th>
<th>Outcome</th>
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<tbody>
<tr>
<td>Akbar et al. 2014</td>
<td>Population: Paraplegic group (PG; n=56): Mean age: 53.0±9.0 yr; Gender: males=44, females=12; Level of lesion: thoracic=50, lumbar=6; Mean time since injury: 34.7±6.8 yr; Able-bodied group (AB): Mean age: 52±10 yr; Gender: males=44, females=12. Intervention: No intervention. Compared functional and structural changes in hand, particularly carpal tunnel syndrome (CTS) in wheelchair dependent paraplegic vs healthy subjects. Outcome Measures: Current pain, CTS symptoms, German version of the disability of the arm, shoulder and hand questionnaire, Phalen’s Test, Tiel’s sign at carpal tunnel, Distal motor latency (DML) measurement, Magnetic Resonance Imaging (MRI).</td>
<td>1. PG experienced significantly more pain in wrist (p=0.004) and trapeziometacarpal joint (p=0.08) CTS symptoms reported more often than AB (p=0.02). 2. CTS was diagnosed by clinical and neurophysiological examination significantly more often in the PG (p&lt;0.05 for both). 3. Mean DML differed significantly between the groups (p&lt;0.001). 4. There was no significant difference in CTS between dominant and non-dominant hands in PG, but was for AB (p=0.01). 5. Women did not present with CTS more often than men in the PG. 6. The relative risk of developing symptoms of CTS was increased 25-fold in the PG over AB (95% CI: 8–81). 7. There was no correlation between the prevalence of CTS and the duration of SCI. 8. Hand function according to the mean disability of the arm, shoulder and hand score was significantly worse in PG than AB (p&lt;0.001). 9. Significantly higher incidences of trapeziometacarpal, radiocarpal and midcarpal osteoarthritis, pathological changes in triangular fibrocartilage complex of right hand in PG right hand (p&lt;0.05 for all). 10. Significantly more flexor tendon sheath and thickening of flexor retinaculum in PG left hand (p&lt;0.05 for both). 11. Relative risk for PG to develop wrist osteoarthritis increased 3.7 times (95% CI: 1–11) on right side, increased 2.8 times (95% CI: 1–9) on left side; developing trapezio-metacarpal osteoarthritis on right side increased 4 times (95% CI: 1–16) and left side by 2.5 times (95% CI:0.6–10).</td>
</tr>
</tbody>
</table>

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). Individuals with paraplegia report much higher rates of carpal tunnel syndrome and pain, compared to able-bodied individuals (Akbar et al., 2014). 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.

**Conclusion**

*There is level 5 evidence (from one observational study; Akbar et al., 2014) that people with paraplegia are significantly more likely to develop bilateral carpal tunnel syndrome.*

Clinicians should be mindful of the risk factors that could influence the development of musculoskeletal pain and consider rehabilitation options accordingly.

**7.0 Reconstructive Surgery and Tendon Transfer**

Reconstructive surgery is one option when trying to improve the function of the hand and upper limb in persons with tetraplegia. Functionally, the benefit of reconstructive surgery may be evident through improved ability to write, complete catheterizations, dress, self-feed, drive, lift objects, button, propel the wheelchair, catch objects overhead, turn in bed, and swim, which are only some of the activities that can become possible after surgery (Rabischong 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 potential benefits, the option to receive reconstructive surgery in persons with SCI is often declined. This decision is influenced by a temporal element including hope for a cure or recovery from SCI (Dunn et al., 2013). It has been recommended that persons with SCI be offered upper limb surgery multiple times throughout their lives to consider changes in perspective. Flexibility of the timing for surgery and the type of rehabilitation offered may also help to increase the uptake of surgery (Dunn et al., 2013).

**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, especially related to the preservation of independence for the individual with tetraplegia (Welraeds et al., 2003). A study by Hanson and Franklin (1976) showed recovery of hand function was preferred to that of the bladder, bowel or even sexual function among persons with tetraplegia. In a survey of tetraplegia 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 as 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).

Despite the many reported studies of hand reconstructive surgery, it is not common practice in many spinal units. Internationally, many barriers for SCI injured individuals exist which results in an underutilization of reconstructive surgery (Fox et al., 2015). The efficacy of surgery to improve hand function still remains controversial (Forner-Cordero et al., 2003). Guttmann (1976), McSweeney (1969) and Bedbrook (1969) believed that only a small percentage of persons with tetraplegia (5%) benefit from hand surgery because they re-adjust the function of their arm and hands if properly rehabilitated, while other authors have estimated that 75% of persons with tetraplegia can benefit from hand surgery (Moberg 1975). A review of epidemiologic data from 1988 to 2000 in the USA found that only seven percent of appropriate surgical candidates actually received surgery (Curtin et al. 2005). In a study completed by Wuolle et al. (2003), individuals with tetraplegia who received upper extremity surgery were surveyed and 70% of the individuals were satisfied with their results and 68% reported improvement in ADLs. These statistics are consistent with physician estimates of 75% of client’s being satisfied, suggesting that both the client and medical professional often view reconstructive surgery as being beneficial and satisfying (Wagner et al., 2007). Reason for underutilization of reconstructive surgery for those with tetraplegia have been identified as; 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; Squitieri and Chung 2008).

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 and has since been modified. The classification takes into account the residual motor strength below the elbow, considering that only the muscles graded four or five according to the Medical Research Council Scale 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-).

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<thead>
<tr>
<th>Motor</th>
<th>Sensory</th>
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<tbody>
<tr>
<td></td>
<td>O-</td>
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<tr>
<td>0</td>
<td>Weak or absent Brachioradialis (BR) ≤ grade 3</td>
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<tr>
<td>1</td>
<td>BR (≥ grade 4)</td>
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<tr>
<td>2*</td>
<td>BR, ECRL</td>
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<tr>
<td>3*</td>
<td>BR, ECRL, ECRB</td>
</tr>
<tr>
<td>4*</td>
<td>BR, ECRL, ECRB, PT</td>
</tr>
<tr>
<td>5*</td>
<td>BR, ECRL, ECRB, PT, FCR</td>
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<tr>
<td>Motor</td>
<td>Sensory</td>
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<tr>
<td><strong>Motor</strong></td>
<td><strong>Sensory</strong></td>
</tr>
<tr>
<td>6* BR, ECRL, ECRB, PT, FCR, Finger Extensors</td>
<td>O- Cu- Total</td>
</tr>
<tr>
<td>7* BR, ECRL, ECRB, PT, FCR, Finger Extensors, Thumb Extensors</td>
<td>- 1 1</td>
</tr>
<tr>
<td>8* BR, ECRL, ECRB, PT, FCR, Finger Extensors, Thumb Extensors, Finger Flexors</td>
<td>1 - 1</td>
</tr>
<tr>
<td>9* Lacks intrinsics only</td>
<td>- 1 1</td>
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<tr>
<td><strong>Total</strong></td>
<td>7 13 20</td>
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</table>

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 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 evaluated. 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 may lack sensitivity and overlook 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 upper limb 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 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 change with time.

### 7.1.1 Pinch

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 13 Reconstructive Surgery – Pinch Studies

<table>
<thead>
<tr>
<th>Author Year Country</th>
<th>Research Design Score Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>McCarthy et al., 1997 USA</td>
<td></td>
<td>Population: Age: 8-58 yr; Gender: males=103, females=30; Level of injury: tetraplegia; Follow-up time: 3-24 mo. <strong>Intervention:</strong> Extrinsic hand reconstruction with intrinsic balancing procedures versus extrinsic reconstructions without intrinsic balancing procedures. <strong>Outcome Measures:</strong> Pre-and postoperative assessments of grip strength (on the second position of the Jamar dynamometer), Activities of Daily Living (ADL).</td>
<td>1. All patients had preoperative grip strength of zero. At an average follow-up period of 31 mo, 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: Five 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 eight 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 improving strength and ADL.</td>
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<td>Author Year</td>
<td>Country</td>
<td>Research Design</td>
<td>Score</td>
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<tr>
<td>House et al. 1992</td>
<td>USA</td>
<td>Case Series</td>
<td></td>
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<tr>
<td>Waters et al., 1985</td>
<td>USA</td>
<td>Case Series</td>
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</table>
Table 14 Summary of Pinch Studies

<table>
<thead>
<tr>
<th>Author</th>
<th>N</th>
<th>Intervention</th>
<th>Main Outcome(s)</th>
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<tbody>
<tr>
<td>McCarthy et al., 1997</td>
<td>135 patients (183 procedures)</td>
<td>Extrinsic reconstruction with Intrinsic Balancing versus without Intrinsic Balancing; FDS Lasso versus Intrinsic Tenodesis for Intrinsic Balancing</td>
<td>+ve grip strength with intrinsic balancing; +ve ADL and functional use; +ve grip strength; +ve ADL and functional use</td>
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<tr>
<td>House et al., 1992</td>
<td>18 patients (21 procedures)</td>
<td>CMC fusion; EPL tenodesis; BR or ECRL or ECRI 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., 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>

Conclusion

*There is level 4 evidence (from two case series studies; House et al., 1992; Waters et al., 1985) that metacarpal fusion can increase pinch strength as well as improve the over all ability to complete daily living tasks.*

*There is level 4 evidence (from one pre-post study; McCarthy et al., 1997) that the addition of intrinsic balancing procedures to extrinsic hand reconstruction can improve pinch strength and the ability to perform daily living tasks compared to extrinsic hand reconstruction alone.*

Increasing pinch strength and the ability to execute daily living tasks is achievable through a variety of surgical interventions such as metacarpal fusion or stabilization.

7.1.2 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-pinache against the side of the middle phalanx of the index finger. Adjustment of tension in these transfers is also completed (Lamb & Chan 1983).

Table 15 Reconstructive Surgery: Pinch and Grip Studies

<table>
<thead>
<tr>
<th>Author Year</th>
<th>Country</th>
<th>Research Design</th>
<th>Score</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
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<tr>
<td>52</td>
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<tr>
<td>Forner-Cordero et al., 2003 Spain Retrospective Follow-up</td>
<td>N_{Initial}=15; N_{Final}=14</td>
<td>Population: Age: 20-62 yr; Level of injury: C4-C7; Time since injury: 15-239 mo.</td>
<td>Intervention: Surgical reconstruction.</td>
<td>Outcome Measures: Increased hand movement and strength, Activities of Daily Living (ADL), Patient's satisfaction, Fulfillment of patient's expectations, Surgical complications.</td>
<td>1. Strength: key-pinache strength average of 17.2 kPa (5-50 kPa); grasp strength average 18.8 kPa (3-45 kPa).</td>
<td>2. No relation found between the ADL test and the key-pinache strength (p=0.7976) or grasp strength (p=0.6948).</td>
</tr>
<tr>
<td>Lo et al., 1998 Canada Case Series</td>
<td>N=9</td>
<td>Population: Level of injury: C5-6; Time since injury: ≥1 yr.</td>
<td>Intervention: Surgery.</td>
<td>Outcome Measures: Not specified.</td>
<td>1. All reported they would have surgery again.</td>
<td>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.</td>
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<tr>
<td>Failla et al., 1990 USA Case Series</td>
<td>N=8</td>
<td>Population: Age: 9-58 yr; Level of injury: tetraplegia.</td>
<td>Intervention: Surgery.</td>
<td>Outcome Measures: Key pinch, Grip strength, Activities of Daily Living (ADL).</td>
<td>1. No statistical results reported-eight patients interviewed, five completed questionnaires.</td>
<td>2. Conclusion-transfer of brachioradialis tendon provides key pinch and grip of sufficient quality to improve the ADLs in patients with loss of flexion of the thumb and fingers.</td>
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<tr>
<td>Author Year</td>
<td>Country</td>
<td>Research Design</td>
<td>Score</td>
<td>Total Sample Size</td>
<td>Methods</td>
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<td>1. Seven extremities had had post deltoid to triceps transfer before opponensplasty; 24 patients, 11 (46%) had bilateral opponensplasty.</td>
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<td>2. Thirty-five opponensplasties were done. 22 flexor tendon transfers were done for voluntary grasp and then opponensplasty.</td>
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<td>3. Fourteen patients (22 extremities) evaluated.</td>
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<td>4. Subjects reported that they would have the operation again (95% of the extremities) and had improved function (91%).</td>
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<td>5. One patient reported that function was unchanged; one was dissatisfied. Overall value of key pinch 35 extremities was 1.47±1.29 kg (mean± SD).</td>
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<td>6. Grasp measured in 20 extremities; 2.81±2.89 kg (mean±SD) (range trace to 10kg).</td>
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<td>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>Kelly et al., 1985</td>
<td>USA</td>
<td>Case Series</td>
<td>N=24</td>
<td></td>
<td>Population: Age: 19-60 yr; Gender: males=17, females=7; Level of injury: group III=3(normal shoulder control, elbow flexion, radial wrist extensors), group IV=11 (same as group III with functioning FCR, PT &amp; triceps, weak fingers), group V=7 (intrinsic hand muscle paralysis), group VI=4 (incomplete paralysis); Time since injury: 1-17 yr; Follow-up time: 1-17 yr.</td>
<td>Intervention: Surgery.</td>
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<td></td>
<td>1. Self-assessment questionnaire results indicated: power decreased since surgery in all patients.</td>
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<td>2. Improved performance of Activities of Daily Living (ADL) was reported.</td>
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<td></td>
<td>1. 6/8 subjects were evaluated. Subjects indicated they were pleased with the surgery.</td>
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<td>2. Hand function tests indicated an improvement (16-49% improvement).</td>
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<td></td>
<td>3. 5/6 subjects showed key grip strength remained constant.</td>
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</tr>
<tr>
<td>Wangdell et al. 2014</td>
<td>Sweden</td>
<td>Observational</td>
<td>N=11</td>
<td></td>
<td>Population: Mean Age: 38.8 yr; Gender: males=10, females=1; Level of Injury: C4=1, C5=2, C6=6, C7=1, Unspecified=1.</td>
<td>Intervention: Patients who underwent hand surgery between February 2009 to March 2011 participated in an interview in order to discuss the individual experiences of regained hand control after grip reconstruction. Interviews were conducted at 12 mo post-surgery at the patients’ home clinic. A grounded theory</td>
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<tr>
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<td></td>
<td>2. During phase one, patients reported experiencing mood swings (both positive and negative) such as fascination, eagerness and fear, encouragement from rehabilitation staff, and practicing their hand control in real life situations with beneficial</td>
<td></td>
</tr>
<tr>
<td>Author Year</td>
<td>Country</td>
<td>Research Design</td>
<td>Score</td>
<td>Total Sample Size</td>
<td>Methods</td>
<td>Outcome</td>
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</tr>
<tr>
<td>Wangdell et al. 2013</td>
<td>Sweden</td>
<td>Observational</td>
<td>N=11</td>
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</tbody>
</table>

approach was adopted for analyzing the interviews.  
**Outcome Measures:** Qualitative analysis, Patient interviews.

results keeping them motivated. Patients transitioned into phase 2 after gaining confidence and belief in trying new activities.

3. At phase 2, establishing hand control in daily life, patients reported diverse learning strategies with some patients using trial and error whilst others planned their activities ahead of time but patients consistently approached one task at a time. Patients also reported that new abilities and tasks required time and effort.

4. External factors in phase 2 were also reported that home environments for practicing activities was more beneficial than a clinic and that positive feedback maintained high motivation levels. A theme emerged in that patients transitioned to phase 3 after developing confidence and self-efficacy in hand control.

5. At phase 3, patients reported the use of celebrations to promote motivation and self-affirmation, changing habits and roles to improve awareness, trusting and using their new skills to become more independent, adapting their physical environment to accommodate their new skills, and that social peers had to allow the patients to use their new skills.

6. After phase 3, a theme emerged of higher independence with patients stating several examples of autonomy.

**Population:** Mean Age: 38.8 yr; Gender: males=10, females=1; Level of Injury: C4=1, C5=2, C6=6, C7=1, Unspecified=1.  
**Intervention:** Patients who underwent hand surgery between February 2009 to March 2011 participated in an interview in order to discuss the individual experiences of regained hand control after grip reconstruction. Interviews were conducted at least 7-17 mo post-surgery.  
**Outcome Measures:** Qualitative analysis, Patient interviews.
4. Psychological aspects that enhanced independence post-surgery included being able to regain privacy and perform self-care tasks alone, and developing a sense of manageability in controlling their own actions which both increased feelings of self-esteem and a decrease in “psychologically bad days”. Further patients reported a sense of identity and a sense of equality (e.g. at work, as a caregiver to children, etc).

Table 16 Summary Pinch and Grip Studies

<table>
<thead>
<tr>
<th>Author</th>
<th>N Intervention</th>
<th>Main Outcome(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forner-Cordero et al., 2003</td>
<td>15 patients (20 limbs) PD to Triceps BR to ECRB Tenodesis of FPL APL to CMC joint or arthrodesis of CMC joint BR or ECRL or PT to EDC and EPL or tenodesis of extensor tendons BR or ECRL or ECRB to FPL PT or ECRL or BR to FDP</td>
<td>+ve key-pinch strength +ve grip strength +ve ADL and functional use +ve patient satisfaction -ve patient expectation</td>
</tr>
<tr>
<td>Meiners et al., 2002</td>
<td>22 patients (23 hands) FCR to FDP ECRL to FDP</td>
<td>+ve lateral and cylindrical grip +ve satisfaction with surgery +ve ADL and functional use</td>
</tr>
<tr>
<td>Lo et al., 1998</td>
<td>8 patients (12 procedures) ERCL to FDP and BR to FPL</td>
<td>+ve satisfaction with surgery +ve key pinch and grip strength +ve ADL functional use</td>
</tr>
<tr>
<td>Failla et al., 1990</td>
<td>8 patients (9 hands) BR to FDP or FPL BR or ECRL to FPL</td>
<td>+ve key-pinch and grip strength +ve ADL and functional use</td>
</tr>
<tr>
<td>Gansel et al., 1990</td>
<td>11 patients 11/11 PT to FDP 10/11 BR to FPL 1/11 BR to FDS</td>
<td>+ve finger flexion +ve key-pinch strength +ve ADL functional use</td>
</tr>
<tr>
<td>Rieser &amp; Waters 1986</td>
<td>9 patients (10 procedures) Tenodesis of FPL, thumb IP joint stabilization 6/9 MP joint tenodesis of extensor tendons of thumb 2/9 BR to wrist extensor 7/9 tenodesis of EPL and EPB</td>
<td>-ve result, bowstringing of FPL across MP joint -ve grasp and lateral pinch strength</td>
</tr>
<tr>
<td>Kelly et al., 1985</td>
<td>24 patients (57 procedures) 7/24 also had PD to Triceps Opponensplasty- FDS to APB Flexor tendon transfers: BR (also used PT, FCR, ECRL, FCU, PL) to FDP 22/35 Flexor tendon transfer BR to FDP (also used PT, FCR, ECRL)</td>
<td>+ve satisfaction with surgery +ve ADL functional use +ve key-pinch, palmar pinch and grip strength</td>
</tr>
</tbody>
</table>
Conclusion

There is level 3 evidence (from one retrospective study; Forner-Cordero et al., 2003) that the outcomes of pinch and grasp reconstructive surgeries overall improve the individuals’ hand function and meet individual expectations.

There is level 4 evidence (from seven case studies; Meiners et al., 2002; Lo et al., 1998; Failla et al., 1990; Gansel et al., 1990; Rieser and Waters, 1986; Kelly et al., 1985; Colyer and Kappleman, 1981) that pinch and grasp reconstructive surgeries are effective in increasing motor function, strength, and grip of the hand. Patients are also report high satisfaction with their surgical results.

Hand reconstructive surgery includes a variety of diverse procedures that allows patients to have improved hand function which results in generally high satisfaction rates with surgical outcomes.

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 17 Reconstructive Surgery – Elbow Extension Studies (Posterior Deltoid to Triceps)

<table>
<thead>
<tr>
<th>Author Year Country</th>
<th>Research Design Score</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population: Mean age: 27 yr; Gender: males=11, females=5.</td>
<td>Straight Arm Raising-statistically significant decrease in maximal shoulder abduction (mean 57 SEM 12 before, 14 SEM 6 after surgery).</td>
<td>1. Straight Arm Raising-statistically significant decrease in maximal shoulder abduction (mean 57 SEM 12 before, 14 SEM 6 after surgery).</td>
<td></td>
</tr>
<tr>
<td>Intervention: Surgery. Control group members sat on a chair, while those with tetraplegia sat in a wheelchair. All were asked to perform two movements; a straight arm lateral and maximal raising and return.</td>
<td>Shoulder flexion increased after deltoid-to-triceps transfer by 42% (mean 113 SEM 11), remained significantly lower (121 SEM 12) than control group (p&lt;0.0001).</td>
<td>2. Shoulder flexion increased after deltoid-to-triceps transfer by 42% (mean 113 SEM 11), remained significantly lower (121 SEM 12) than control group (p&lt;0.0001).</td>
<td></td>
</tr>
<tr>
<td>Outcome Measures: Straight Arm Raising, Hand-to-nape-of-neck movement.</td>
<td>Hand-to-nape-of-neck-movement-no significant improvements were noted after surgery.</td>
<td>3. Hand-to-nape-of-neck-movement-no significant improvements were noted after surgery.</td>
<td></td>
</tr>
<tr>
<td>Peaks of shoulder and elbow flexion speed are almost normal, indicating</td>
<td>Peaks of shoulder and elbow flexion speed are almost normal, indicating</td>
<td>4. Peaks of shoulder and elbow flexion speed are almost normal, indicating</td>
<td></td>
</tr>
<tr>
<td>Author Year Country</td>
<td>Research Design</td>
<td>Score Total Sample Size</td>
<td>Methods</td>
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<tr>
<td>Dunkerley et al., 2000 UK Case-Control N&lt;sub&gt;Initial&lt;/sub&gt;=15; N&lt;sub&gt;Final&lt;/sub&gt;=11</td>
<td>Population: Age: 23-38 yr; Time since injury: 5-16 yr. Intervention: Surgery. Outcome Measures: Questionnaire, Functional independence measure (FIM), 10m push, Figure of 8 push.</td>
<td>the importance of restoring elbow extension torque for improving the whole kinematic picture of the upper limb.</td>
<td>1. Both groups scored identically on the FIM. 2. No significant differences in mobility were noted (p=0.256, and p=0.432). Questionnaire was answered only by the treatment group; clients gave positive response to the questions.</td>
</tr>
<tr>
<td>Rabischong et al., 1993 France Prospective Controlled Trial N=20</td>
<td>Population: Mean age: 33.6 yr; Level of injury: C6; Time since injury: 28-173 mo. Intervention: 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.</td>
<td>1. The muscle was tested at six different lengths (130°, 110°, 90°, 70°, 45° and 0° of elbow flexion) with the shoulder abducted at 90°. 2. When compared, the absolute values (dimension of torque) were significantly different between groups (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° in experimental group and 110° in control group with a plateau between 110° and 70°. Length-tension relationship was fairly similar among control group, but great differences in experimental group.</td>
<td></td>
</tr>
<tr>
<td>Lacey et al., 1986 USA Case Series N=10</td>
<td>Population: Level of injury: C6-C7; Mean time since injury: 24 mo. Intervention: Surgery. Outcome Measures: Not specified.</td>
<td>1. No statistically significant differences between pre-and post-operative stages. Activities that were noted as improved were: the overhead use of the arms, use of arms while lying supine and eating.</td>
<td></td>
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<tr>
<td>Raczyka et al., 1984 USA Case Series N&lt;sub&gt;Initial&lt;/sub&gt;=22; N&lt;sub&gt;Final&lt;/sub&gt;=18</td>
<td>Population: Time since injury: 10-242 mo. Intervention: Surgery. Outcome Measures: Activities of Daily Living (ADL), use of wheelchair.</td>
<td>1. 15/18 reported function improvement after surgery, 13 felt they gained an increase in independence. 2. Functional improvements and grooming was noted. 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.</td>
<td></td>
</tr>
<tr>
<td>Robinson et al. 2014 UK Post-Test N=10</td>
<td>Population: Tetraplegic Group (n=5): Mean age: 39±6 yr; Gender: males=5, females=0; Level of injury: C5=4, C5/6=1; Mean time since injury: 17.6 yr; Severity of Injury: AIS A=3, AIS B=1, AIS C=1. Control group (n=5): Mean age: 38±7 yr; Gender: males=5, females=0.</td>
<td>1. The percentage of trials containing a sub-movement did not differ significantly between the tetraplegic and control groups (p&gt;0.1). 2. For % of type 3 sub-movements, there was a significant for direction (p&lt;0.05), indicating that both groups</td>
<td></td>
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</tbody>
</table>
Intervention: Aiming movements were performed in two directions (20 cm away or toward), with or without vision with a ball transfer unit by both SCI patients and age-matched neurotypical controls. Trials that contained a sub-movement phase (i.e., discontinuity in velocity, acceleration or jerk) were identified.

Outcome Measures: Kinematic variables, Frequency and distribution (velocity, acceleration or jerk discontinuity), Amplitude and duration of sub-movements.

1. Intervention: Aiming movements were performed in two directions (20 cm away or toward), with or without vision with a ball transfer unit by both SCI patients and age-matched neurotypical controls. Trials that contained a sub-movement phase (i.e., discontinuity in velocity, acceleration or jerk) were identified.

2. Outcome Measures: Kinematic variables, Frequency and distribution (velocity, acceleration or jerk discontinuity), Amplitude and duration of sub-movements.

3. A significant effect was shown in direction for movement time (p<0.05) and a condition × direction × group interaction for both movement time (p<0.01) and peak velocity (p<0.05).

4. Peak acceleration indicated significance for group and direction (p<0.02).

5. Primary movement amplitude was greater when aiming away from than toward the body (p<0.05); this difference was somewhat larger in the vision than no vision condition (p<0.05).

6. Amplitude revealed significance of group, with tetraplegics making larger corrections than controls (p<0.05).

7. No significant for duration of corrective sub-movements between groups (p=0.08).

8. Magnitude of spatial variability at peak velocity in sub-movement trials showed significance in group (p<0.05) as well as condition × direction × group interaction (p<0.05).

9. Both groups made a greater percentage of functional than non-functional corrections when aiming toward, irrespective of vision (p<0.01).

Table 18 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>
<tr>
<td>Raczkow et al., 1984</td>
<td>18 pt 19 transfers</td>
<td>PD to triceps</td>
<td>+ve elbow extension strength +ve ADL and functional use</td>
</tr>
<tr>
<td>Robinson</td>
<td>= submovement % +ve amplitude for paraplegic +ve functional corrections</td>
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</table>
Conclusion

There is level 2 evidence (from one prospective control trial; Rabischong et al., 1993) that surgery can increase rotation in the elbow and the relationship with peak torque.

There is level 3 evidence (from one case-control; Dunkerley et al., 2000) that PD to triceps surgical intervention can have limited/similar results to controls when examining functional outcome.

There is level 4 evidence (from two case series; Lacey et al., 1986 and Raczka et al., 1984) that PD to tricep surgery can have a positive effect on functional use as well as result in positive patient satisfaction with surgery.

There is level 4 evidence (from one pre-post study; Remy-Neris et al., 2003) that restoring elbow extension is important for over all upper limb kinematics, however surgical interventions can have limited results.

<table>
<thead>
<tr>
<th>Author Year</th>
<th>Country</th>
<th>Research Design</th>
<th>Score</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mulcahey et al., 2003</td>
<td>USA</td>
<td>RCT</td>
<td>PEDro=6</td>
<td>N=9</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.</td>
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<td>Intervention: Surgery.</td>
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<td></td>
<td>Outcome Measures: Muscle strength, Flexion torque, Modified University of Minnesota Tendon Transfer Functional Improvement Questionnaire, Canadian Occupational Performance Measure (COPM), Activities of Daily Living (ADL).</td>
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<td>4. No significant difference between the groups was found for elbow flexion torque (47% reduction in torque after two yr versus baseline).</td>
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<td></td>
<td>5. Following surgery, 48/63 elbow extension ADL did not improve in</td>
</tr>
<tr>
<td>Author Year</td>
<td>Country</td>
<td>Research Design</td>
<td>N</td>
<td>Intervention</td>
<td>Main Outcome</td>
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</tr>
<tr>
<td>Kozin et al., 2010</td>
<td>USA</td>
<td>Case Series</td>
<td>40 patients</td>
<td>Biceps to Triceps</td>
<td>+ve elbow extension strength, +ve reaching overhead, Improvement in one goal on Canadian Occupational Performance Measure (COPM) for each patient</td>
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<td></td>
<td>36 left; 32 right elbow surgeries</td>
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</tr>
<tr>
<td>Mulcahey et al., 2003</td>
<td>USA</td>
<td>Case Series</td>
<td>9 patients</td>
<td>Biceps to Triceps</td>
<td>+ve elbow extension from either surgery</td>
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<td>16 elbows</td>
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</tbody>
</table>

Table 20 Summary Reconstructive Surgery - Elbow Extension Studies (Biceps to Triceps Transfer)

Population: Mean age: 17.3 yr; Level of injury: C5=10, C6=29, C7=1.

Intervention: Surgery for a biceps to triceps tendon transfer (36 left, 32 right).

Outcome Measures: Manual muscle testing, Canadian Occupational Performance Measure (COPM).

1. Manual muscle testing for elbow extension revealed a statistically significant increase in preoperative to postoperative muscle strength (p<0.001).
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 COPM was observed by each patient.
7. COPM total mean score statistically increased from 2.6 to 5.6 and from 1.8 to 5.7 for performance (p<0.001) and satisfaction (p<0.001), respectively.

Kuz et al., 1999
USA
Case Series
N=3


Intervention: 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.
Conclusion

There is level 2 evidence (from one RCT; Mulcahey et al., 2003) that biceps to triceps surgery can increase elbow extension strength, reaching, and overall performance improvement.

There is level 4 evidence (from two case series; Kozin et al., 2010; Kuz et al., 1999) that elbow extension surgery improves elbow extension and overall functionality of the joint.

Elbow extension surgery has strong positive outcomes and should be considered as a viable option for those with limited extension which impacts daily living.

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

Table 21 Reconstructive Surgery – Multiple Reconstructions

<table>
<thead>
<tr>
<th>Author &amp; Year</th>
<th>Country</th>
<th>Research Design</th>
<th>Score</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friden et al., 2012a</td>
<td>Sweden</td>
<td>Pre-post</td>
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</tbody>
</table>

Population: Age range: 19-70 yr; Type of SCI: traumatic=12, non-traumatic=3; Level of injury: tetraplegia=15, paraplegia=0; Mean time since injury: 54.2±42.8 mo; International classification of patients’ upper extremities: OCu4-OCu8.

Intervention: All patients had their extensor 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, Active finger range of motion (ROM).

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 (SEM 0.8) cm in six patients who had active thumb-index distance of 6.3 (SEM 1.6) cm before surgery.
3. 14/15 patients were able to direct and coordinate key pinch and perform tasks using restored APB function including five patients whose EDM strength was rated as grade 3 before the transfer.
<table>
<thead>
<tr>
<th>Author Year Country</th>
<th>Research Design</th>
<th>Score</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friden et al., 2012b, Sweden</td>
<td>Case Control</td>
<td>N=12</td>
<td></td>
<td>Population: Treatment group (n=6): Mean age: 32.2±4.9 yr; Gender: males=4, females=2. Control group (n=6): Mean age: 31.2±5.0 yr; Gender: males=4, females=2. Intervention: 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, Pronation range of motion (ROM).</td>
<td>9. Post-operative active pronation was significantly greater in the dorsal transfer group in comparison to the palmar group (149±6° and 75±3°, respectively). 10. Pinch strength was similar between both groups (1.28±0.16 kg and 1.20±0.21 kg), respectively. 11. It is feasible to reconstruct lateral key pinch and forearm pronation simultaneously using only the BR muscle.</td>
</tr>
<tr>
<td>Rothwell et al., 2003, New Zealand</td>
<td>Case Series</td>
<td>N=29; NFinal=24</td>
<td></td>
<td>Population: Mean age: 42.9 yr; Mean time since injury: 20.5 yr; Mean time since surgery: 15.1 yr; Handedness: right=22, left=24; Level of Injury: 01: 6 hands; 02: t3 hands; 03: 5 hands; 0Cu2: 2 hands; 0Cu3: 6 hands; 0Cu4: 17 hands; 0Cu5: 8 hands; 0Cu6: 1 hand; tetraplegia. Intervention: Surgery. Outcome Measures: Lamb and Chan questionnaire with additional 10 Burwood questions, Swanson sphygmomanometer (SGM) (hook grip), Preston Pinch Meter (key pinch), Quadriplegic index of Function (QIF), Digital Analyzer (DA) (key and grip pinch).</td>
<td>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&lt;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&lt;0.001); average pinch strength 18 left thumbs decreased from 17.7-8.8 N (significant decrease p&lt;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 versus 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&lt;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 42.1-60.2 mm Hg (p&lt;0.001) and pinch grip increase from 24.0-38.4 N in 31 thumbs that had active transfers using 2001 DA data (p=0.03). Hook strength obtained from a tenodesis in seven 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>
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<tr>
<td>Author Year Country</td>
<td>Research Design</td>
<td>Methods</td>
<td>Outcome</td>
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<td>5. Questionnaire results; Lamb and Chan activity measure: showed perceived improvement of functional activities significantly lower in 2001 (p&lt;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).</td>
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<tr>
<td>Welraeds et al., 2003 Belgium</td>
<td>Case Series</td>
<td>N=25</td>
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<tr>
<td>Population: Mean age: 37 yr; Level of injury: C5-C8; Time since injury: 7-356 mo.</td>
<td>Intervention: Upper limb surgery.</td>
<td>Outcome measures: Functional testing.</td>
<td>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.</td>
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<tr>
<td>Freehafer 1998 USA</td>
<td>Case Series</td>
<td>N=285</td>
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<tr>
<td>Population: Level of injury: C5-C8.</td>
<td>Intervention: Surgical reconstruction.</td>
<td>Outcome Measures: Not specified.</td>
<td>1. Oponens transfers were done 180 times; transfers for finger flexion-161 times; posterior deltoid-transfers-59 times; transfers for wrist extension-17 times. 2. 13 out of 285 stated that they were no better, and no patient said they were worse.</td>
<td></td>
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<tr>
<td>Mohammed et al., 1992 New Zealand</td>
<td>Case Series</td>
<td>N=57</td>
<td></td>
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<tr>
<td>Population: 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.</td>
<td>Intervention: Surgery.</td>
<td>Outcome Measures: Activities of Daily Living (ADL), Preston Pinch Meter, Hook-grip strength, Elbow extension.</td>
<td>1. Subjective Assessment: obtained for 86% of the patients, av. Follow up of 37 mo (range 5-86 mo); 70% reported good or excellent results; 22% fair; 8% poor. 2. Simultaneous surgery for key-grip and hook grip strength: 96% good or excellent results. 3. Objective Results: over 70% of patients, av. follow up of 32 mo; Key Pinch 52/68 cases (76%); av. strength was 2.1 kg. Hook grip measured in 42/58 cases (72%), thumb included av. strength was 42 mmHg; thumb excluded 29 mmHg. 4. Elbow extension measured in 71% of patients, obtained grade 3 or 4 strength.</td>
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<tr>
<td>Ejeskar &amp; Dahllof 1988 Sweden</td>
<td>Case Series</td>
<td>N=43</td>
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<tr>
<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.</td>
<td>Intervention: Surgery.</td>
<td></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.</td>
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<tr>
<td>Author Year</td>
<td>Country</td>
<td>Research Design</td>
<td>Score</td>
<td>Total Sample Size</td>
<td>Methods</td>
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<tr>
<td>Freehafer et al., 1984 USA</td>
<td>USA</td>
<td>Case Series</td>
<td>68</td>
<td>142 transfers were performed on 68 subjects.</td>
<td>Key Grip: 50 hands/40 patients; Strength 0-3.5 kg (av. 0.7 kg); 15 cases had minimum of 1.0 kg.</td>
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<td>2. No upper limbs were made worse.</td>
<td>Finger Flexion: 14 hand/13 patients (ECRL to profundus II-V); grip 0-0.27 kP (av. 0.13 kP); 5/14 minimum strength 1.0 kg.</td>
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<td></td>
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<td>3. Four remained unimproved, all others that had tendon transfers improved.</td>
<td>Four 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>Lamb &amp; Chan 1983 UK</td>
<td>UK</td>
<td>Case Series</td>
<td>41</td>
<td>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.</td>
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<td>2. Hand Function: 48 hands (assessed only 27 patients). 5 rated as excellent; 26 rated good; 11 rated as fair; 4 graded as poor. No patient had any impairment of hand function after operation.</td>
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<td>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 interests.</td>
<td></td>
</tr>
<tr>
<td>Hentz et al., 1983 USA</td>
<td>USA</td>
<td>Case Series N&lt;sub&gt;Initial&lt;/sub&gt;=30; N&lt;sub&gt;Final&lt;/sub&gt;=23</td>
<td></td>
<td>Elbow Function:</td>
<td>Reconstruction of key grip and active elbow extension.</td>
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<td></td>
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<td></td>
<td></td>
<td>and active elbow extension.</td>
<td>Objective measurements - pre + post op strength, Range of motion (ROM)</td>
</tr>
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<td>Outcome Measures: Interview and/or questionnaire (self-care, communication, mobility), Objective measurements - pre + post op strength, Range of motion (ROM)</td>
<td>2. Subjective client reports.</td>
</tr>
<tr>
<td>Author Year Country</td>
<td>Research Design</td>
<td>Score</td>
<td>Total Sample Size</td>
<td>Methods</td>
<td>Outcome</td>
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<tr>
<td>Gregersen et al. 2015 Denmark Post Test N=40</td>
<td>Population: Median Age: 48 yr; Gender: males=33, females=7; Level of Injury: C4=7, C5=14, C6=12, C7=6, C8=1; Severity of Injury: AIS A=25, AIS B=9, AIS C=3, AIS D=3. Intervention: Patients completed a questionnaire on general satisfaction, independence, activities of daily living (ADL), appearance, reliability of the surgery, postoperative therapy, and life impact since undergoing upper extremity surgery post-SCI. Patients were also asked to write a list of activities that they performed better/worse and if they needed fewer aids post-surgery. A total of 102 surgical procedures had been performed including pinch/thumb stabilization (n=46), elbow extension posterior deltoid to triceps (n=20), hand grasp/finger flexion (n=14), wrist extension (n=7), Zancolli (n=7), freehand (n=3), and miscellaneous (n=5). Assessments were conducted at post-treatment. <strong>Outcome Measures</strong>: Custom satisfaction survey.</td>
<td>of wrist + elbow extension, Strength of key pinch, Range of passive wrist flexion + functional testing.</td>
<td>1. The mean percentage for positive responses (strongly agree/agree) was 76% for general satisfaction and 84% for life impact. 2. Appearance of the patients’ hand(s) was scored relatively lower with only 28% reporting an improvement in appearance post-surgery and 49% were unsatisfied. 3. Positive responses were reported in 73% of patients for improvements in ADL with 85% reporting that ADL had become easier and 58% reporting that activities could be performed faster after surgery. 4. Patients who had received surgery between the yr 1991-2008 reported greater levels of general satisfaction and ADL than patients who had received surgery between the yr 1973-1990 (both p&lt;0.001). 5. When comparing patients who had elbow extension or pinch/thumb surgery as the only procedure, patients who had received elbow extension surgery reported significantly greater levels of satisfaction regarding ADL (p=0.027) and independence (p&lt;0.001). 6. Patients reported that eat and drinking, grasping and coordination, dressing/undressing, stretching, and using tools were easier after surgery.</td>
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<tr>
<td>Dunn et al. 2014 New Zealand Cohort N=19</td>
<td>Population: Mean Age: 53 yr; Gender: males=18, females=1; Level of Injury: C5=3, C6=9, C7=7. Intervention: Patients who had received tendon transfers between 1982-1991 were followed up as part of a longitudinal study. Surgical procedures included brachioradialis (BR) to flexor pollicis longus (FPL; n=27, 31%), extensor carpi radialis longus (ECRL) to flexor digitorum profundus (FDP; n=20, 23%), elbow extension (n=18, 21%), BR to FDP (n=7, 8%), FPL tenodesis (n=6, 7%), pronator teres (PT) to FPL (n=4, 5%), and FDP tenodesis (n=4, 5%). Assessments were conducted 11yr after previous follow-up. <strong>Outcome Measures</strong>: Lamb &amp; Chan questionnaire (LCQ), Key pinch strength, Grip strength, Type of wheelchair used.</td>
<td></td>
<td>1. Only patients who had undergone a left-side tenodesis reported a significant improvement in key pinch strength (p=0.04) from the previous follow-up (2001) to current follow-up (2012). 2. No significant differences were reported between patients who had undergone active transfer or tenodesis at current follow-up. 3. The active transfer patients declined by 8% (left side) and 5% (right side), but left and right side tenodesis grip strength increased by 70% and 32%, respectively (both p&lt;0.05) from previous follow-up to current follow-up. 4. Although the majority of the items on the LCQ were unchanged from the previous follow-up to current follow-up,</td>
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</table>
Table 22 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-pin 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 (48 reconstructions)</td>
<td>BR to FPL or BR and tenodesis FPL ECRL to FDP PD to Triceps</td>
<td>+ve key-pin and hook grip +ve ADL and functional use</td>
</tr>
<tr>
<td>Welraeds et al., 2003</td>
<td>25 patients (43 procedures)</td>
<td>PD to Triceps ECRL to FDS BR to FDS</td>
<td>+ve elbow extension +ve key grip and grasp +ve ADL and functional use</td>
</tr>
<tr>
<td>Author</td>
<td>N</td>
<td>Intervention</td>
<td>Main Outcome(s)</td>
</tr>
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<td>--------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Mohammed et al., 1992</td>
<td>57 patients</td>
<td>PD to Triceps: 59 times Transfers for wrist extension: 17 times</td>
<td>+ hook grip strength +ve ADL and functional use</td>
</tr>
<tr>
<td>Ejeskar &amp; Dahllof 1988</td>
<td>43 patients</td>
<td>PD to Triceps Key-Pinch: BR or PT to ECRL; FPL tenodesis and IP stabilization Hook Grip: BR or ECRL to FDP</td>
<td>-ve elbow extension +ve key-grip and finger flexion +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 +ve elbow extension +ve ADL and functional use</td>
</tr>
<tr>
<td>Lamb &amp; Chan 1983</td>
<td>41 patients</td>
<td>PD to Triceps Biceps to Triceps Hand Grip: ECRL to FDP BR to FPL Key-Pinch: FPL tenodesis or FPL tenodesis plus ECRL to FDP Other: EPB to ECU, FCR to FDS, APB to EDM</td>
<td>+ve elbow extension and function -ve elbow extension (biceps to triceps) +ve hook grip and key pinch and ADL and functional use</td>
</tr>
<tr>
<td>Hentz et al., 1983</td>
<td>30 patients</td>
<td>PD to Triceps or Biceps to Triceps FPL tenodesis BR to ECRB EPL and EPB tenodesis</td>
<td>+ve satisfaction with surgery +ve pinch and grip strength</td>
</tr>
<tr>
<td>Gregersen et al., 2015</td>
<td>40 patients</td>
<td>Pinch/Thumb stabilization Deltoid to triceps Hand grasp Wrist extension Freehand</td>
<td>+ve satisfaction with surgery +ve life impact +ve ability for perform ADL</td>
</tr>
<tr>
<td>Dunn et al., 2014</td>
<td>19 patients</td>
<td>BR to FPL ECRL to FDP BR to FDP FPL FDP</td>
<td>+ve improvement in pinch strength for left sided tenodesis = outcome for active transfer vs tenodesis -ve decline for active transfer patients +ve increase in grip strength for tenodesis -ve decline for functionality and use of wheelchair</td>
</tr>
<tr>
<td>Friden et al. 2014</td>
<td>11 patients</td>
<td>FPL transfer Distal thumb tenodesis Extensor carpi radialis longus-to-flexor digitorum profundus transfer Intrinsic balancing Activation of thumb abduction Arthrodesis Deltoid to triceps transfer</td>
<td>+ve pinch strength +ve grip strength +ve increase in max thumb to finger distance Anti-gravity elbow extension was restored in one patient</td>
</tr>
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Discussion

In reviewing the identified studies, 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, the subjective acceptance among patients who have had reconstructive surgery is high (Gregersen et al., 2015). 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 surgery or the use of neuroprostheses is beneficial to the client as new movement strategies have to be relearned to perform ADL (van Tuijl et al., 2002), however, surgeries occurring more recently have been associated with greater satisfaction and ability to perform ADLs (Gregersen et al., 2015).

Conclusion

There is level 4 evidence (from one pre-post study; Friden et al., 2012a) that multiple reconstructions can improve key-pincher and grip strength.

There is level 3 evidence (from one case-control study; Friden et al., 2012b) that patients who had multiple stage BR to FPL through the interosseous membrane had significantly greater active pronation, while other measures remained similar.

There is level 4 evidence (from nine case series; Rothwell et al., 2003; Welraeds et al., 2003; Freehafer, 1998; Mohammed et al., 1992; Ejeskar and Dahllof 1988; Freehafer et al., 1984; Lamb and Chan, 1983; Hentz et al., 1983; Friden et al., 2014) that multiple reconstructive surgery over all increases motor function as well as the ability to perform daily living tasks.

There is level 4 evidence (from one post-test; Gregersen et al., 2015) that a variety of reconstructive surgeries can be used to improve overall elbow function and strength.

There is level 2 evidence (from one cohort study; Dunn et al., 2004) that active transfer procedures may have little benefit over tenodesis procedures as the rate of decline post-surgery is greater and other functional outcomes are equal.

Multiple concurrent reconstructive surgery appears to improve pinch, grip, and elbow extension functions that improve both ADL performance and quality of life in tetraplegia. However, active transfer seems to be the least successful of these procedures.
8.0 Nerve Transfers

Recently, the surgical procedure of nerve transfers is evolving as an alternative procedure 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).

Nerve transfers have traditionally been performed for brachial plexus injuries. More recently, the development of brachialis to the anterior interosseous nerve transfer for SCI has been applied (Hawasli et al., 2015).

Senjaya and Midha (2013) and Midha (2004) described the fundamental principles, advantages and potential drawbacks of nerve transfers when compared to tendon transfers in a review article. They state that 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. Furthermore, that the donor nerve should be from a muscle whose function is expendable or has redundant innervation and that the nerve repair should be performed directly without intervening grafts. It is highly recommended that a donor muscle with pure motor fibers be used to maximize the muscle fiber re-innervation, while also ensuring the donor nerve should have a large number of motor axons and be a reasonable size match to the recipient nerve. Lastly, 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. Clinicians should also be mindful that motor re-education improves functional recovery post operatively.

Advantages over Tendon Transfers

Nerve transfers have many advantages over tendon transfers. Tendon transfers require significantly more dissection and extended post-operative limb immobilization while the tendon heals (Brown 2012). There is also less surgical scarring in common areas of the hand where tendons overlap anatomically, thus fewer chances of restricted motion (Keith & Peljovich 2012). Reconstruction of finger flexion and extension must be done in separate phases, owing to conflicting positions for postoperative immobilizations (Revol et al., 2002) which may be 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). Also, tenotomy may cause detrimental effects on muscle function owing to the fact that reduced specific force is developed (Guelinekx et al., 1998). In general nerve transfers take a shorter period of less restrictive immobilization probably with less pain, minimal loss of donor muscle function (Brown 2012). 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).
Nerve transfers compared to tendon 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, 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). Lastly, nerve transfers can be accomplished
without appreciable loss of function from the donor muscle group because nerve
transfers 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 five
times 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.

**Potential Drawbacks of Nerve Transfers**

There are also a few potential drawbacks of nerve transfers (Senjaya & Midha 2013).
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 intended
function. An entirely denervated muscle, as a result of its nerve being donated is no
longer suitable for muscle transfer donor. 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 nerves.

**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 and
mapping muscles to identify functionality. The extent of LMN injury at the injured
metamere should be assessed and each key muscle group evaluated to determine the
following: type of motor neuron injury (LMN, UMN) by evaluating tone, trophic status,
deep tendon reflex, joint ROM and deformities and electrodiagnostic studied are
beneficial to determine extent of SCI. After a careful and complete evaluation of the
LMN injury, mapping the relevant muscles should be conducted to categorize muscles
in one of three ways: functional muscles (innervated by suprasesional segments),
paralyzed and denervated muscles (innervated by injured metamere with damage to
LMN), and paralyzed but innervated muscles (innervated by infraslesional segment, with
preserved LMN).
The next assessment to be made is to decide what primary function to restore. 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 six months. Re-innervation of muscle innervated by infralesional segment is not time-dependent and can performed years after injury (Bertelli et al., 2011).

### Table 23 Nerve Transfers

<table>
<thead>
<tr>
<th>Author Year</th>
<th>Country</th>
<th>Research Design</th>
<th>Score</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
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<tbody>
<tr>
<td>Fox et al. 2015a</td>
<td>USA</td>
<td>Case Series</td>
<td>N=9</td>
<td></td>
<td>Population: Mean Age: 32.9 yr; Gender: males=7, females=1.</td>
<td>1. Functional gains were reported from 6mos onwards according to patient self-reports which included increased grasp strength (n=2), an increased use of their hand for feeding (n=2), an increase in wrist stability (n=1), and improvement in pinch activities (n=1). 2. Three patients reported no changes or improvements since surgery. 3. All patients achieved grades of 1-3 on the MRC indicating a trace of contraction, active movement with gravity eliminated, and active movement against gravity respectively. 4. Complications post-surgery included paresthesias of the thumb (n=3), urinary tract infection with sepsis (n=1), and seroma (n=1).</td>
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<tr>
<td>Fox et al. 2015b</td>
<td>USA</td>
<td>Cohort</td>
<td>N=7</td>
<td></td>
<td>Population: Mean Age: 28 yr; Gender: males=6, females=1; Level of Injury: C4=2, C5=2, C6=3; Severity of Injury: AIS A=4, AIS B=2, AIS C=1.</td>
<td>1. Histomorphometric analysis revealed excellent functioning of the transferred nerves. 2. One patient experienced a reduced fiber density, heterogeneity of fibers, and imperfect architecture of the nerve cell after histomorphometric analysis, however, this patient was found to have low motor neuron involvement at the time of surgery. 3. No patients experienced a decline in postoperative functioning compared to baseline functioning according to MRC scores. 4. One patient who underwent deltoid-to-triceps transfer experienced postoperative weakness of the deltoid (MRC grade 4) but eventually subsided</td>
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</tbody>
</table>
Table:

<table>
<thead>
<tr>
<th>Author Year</th>
<th>Country</th>
<th>Research Design</th>
<th>Score</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bertelli et al. 2015</td>
<td>Brazil</td>
<td>Post-Test</td>
<td>N=7</td>
<td></td>
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</tbody>
</table>

Methods:

- were conducted at baseline and at 2, 4 and 12 wk post-surgery.
- **Outcome Measures:** Medical Research Council elbow flexion grade (MRC), Histomorphometric analysis, Complications post-surgery, Functional gains reported by patients.

Outcome:

- and strength returned to baseline levels (MRC grade 5).
- Functional gains as according to patient self-reports included an improvement in grasp strength (n=2), greater wrist stability (n=1), an improvement in pinch activity (n=1), and greater use of their hand for activities such as feeding and using a cell phone (n=1).
- Two patients did not report any changes in functioning from pre-surgery to post-surgery.
- Four patients experienced minor complications including paresthesia of the thumb (n=2), hypesthesia of the thumb (n=1), and a seroma which required drainage (n=1).
- Two patients experienced major complications including urosepsis (n=1) and a urinary tract infection (n=1).

Population:

- Mean age: 26 yr; Gender: males=6, females=1; Level of injury: complete C-6=7; Mean ASIA motor score: 15.8±3.9; Mean time since injury: 7 yr.

Intervention:

- 27 recipient nerves. Elbow, thumb and finger extension reconstruction via nerve transfer was performed on patients with midcervical spinal cord injuries on average 7 mo post injury and outcomes were reported.

Outcome Measures:

- British Medical Research Council scale (BMRC).

Discussion:

Restoration of elbow extension function is an integral part of upper extremity 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 has 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). To 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.

Case studies and feasibility trial have comprised the studies that have applied brachialis to the anterior interosseous nerve transfer for SCI. These studies support the feasibility and safety of these nerve transfers, yet, perioperative complications were present for some patients (Fox et al., 2015b). Continued research on the transfer of the brachialis to the anterior interosseous nerve for the treatment of tetraplegia after a cervical SCI with larger samples will be beneficial to determine the potential for improving hand function while also considering the consequences of this surgery (Hawasli et al., 2015). Future research should also investigate the optimal timing for surgeries and the combination of traditional treatment options and nerve transfers (Fox et al., 2015a).

**Conclusion**

*There are only a few 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 (from one case series; Fox et al., 2015a) that nerve transfer surgery can increase functionality and grasp strength in some patients, however not all patients have successful surgical outcomes.*

*There is level 2 evidence (from one cohort study; Fox et al., 2015b) that the risk of negative outcomes, such as postoperative decline compared to baseline, for nerve transfer surgery are low.*

*There is level 4 evidence (from one post-test study; Bertelli et al., 2015) that nerve transfer surgery can increase motor hand function without compromising donor site function in patients with midcervical spinal cord injuries.*

With greater satisfaction and lower risks reported since 1990, nerve transfer surgery to restore hand and upper limb function in persons with tetraplegia is emerging as another viable 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 but may be an area of future research. The next generation of neuroprosthetic systems are currently being developed with the goal of integrating fully implantable multi-channel stimulators and feedback sensors with adaptive control systems (Grahn et al., 2014).

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 when considering an implantable neuroprosthesis. Their considerations for selection cover a broad range of factors from physical to
psychosocial and should be considered for patient selection. Anatomical factors are important for the physical stability of the implant, it is recommended that the patient have stable tetraplegia with C5 or C6 motor level with international classification motor scores of zero, one, two or an impairment scale level of A, B, C (AIS). Physiological conditions considered should be the presence of adequate ROM in joints of the shoulder, arm, forearm, wrist and hand for the type of prosthesis. Medically, it is generally recommended that patients be free of overwhelming medical problems. Sufficient motivation to learn and use the prosthesis is also critical, as well as knowing the level of support available from caregivers or family members, so psychosocial factors must also be considered. The individual should exhibit certain indirect needs which would impact the success of the implant, such as sufficient vision, and cognitive ability to incorporate visual feedback and progress in the learning of the prosthesis. Lastly, functional recovery should plateau before the consideration of a neuroprosthesis, which usually occurs at one-year post-injury.

Contraindications to neuroprothesis use include cardiac disease, arrhythmias, pacemakers, chronic systemic infections, diabetes, and immune disease.

An important barrier to the use of neuroprothesis is the lack of commercially available devices. Despite the demonstrated effectiveness of neuroprothesis for improving hand function and quality of life only one device is currently available commercially (Venugopalan et al., 2015). Three studies of unique devices have been considered in SCI injured individuals.

**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.

**Clinical Results of Neuroprostheses**

There are many reported clinical results of neuroprosthesis use. Some focus on patient outcome and improvement while others focus on the efficacy of a specific model of prosthesis. Currently, clinical trials show improvement in the following areas in stroke and SCI patients; grasping, functional ability of upper extremities, and motor control. FES technology specifically facilitates a comfortable and secure grasp that allows the individual to hold and manipulate various objects. In terms of specific outcomes based on the model of prosthetic used, all except the Bionic Glove were able to facilitate both palmar (power) grasp and lateral (fine) grasp. While 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. 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. In general, 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. A usual time delay of one to two seconds from the time the command is issued to the moment the grasp is executed is common. This restricts the speed that an individual can grasp and release objects and therefore neuroprostheses for grasping can only be used for slower grasping tasks.

**Challenges in Neuroprosthesis Use and Reasons for Not Using Neuroprosthesis**

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 can also overestimate the results that assistive systems can provide and therefore may not be satisfied with the final outcome. The acceptance of the device depends on the specific needs of the client and their specific expectations and limitations should be considered. The success of implantation can also be complicated by variety of age and lifestyle factors represented in patients with UE paralysis, this can also limit the number of individuals willing to consider neuroprostheses. Clients can also have a series of intrinsic motivations for not pursuing a prosthetic, such as they may be waiting for a cure for their illness, afraid of the technology, poor motivation, and an unwillingness to devote considerable attention to the everyday use of it. In order for an individual to consier a prosthesis they must themselves feel comfortable with the technology, and using it in a variety of settings, such as the home and work environment. Other potential barriers to the acceptance of a prosthesis can include technical difficulties, cultural differences, and pre-existing psychological perceptions. Then there are the specific limitations associated with the device itself, some models (FES technology) require intensive maintenance through a skilled technician, there can be inadequate reliability of use (breaking of wires orelectrode failure), implantion often requires additional surgeries, and lastly that extensive training is required to use the device. There is also an ongoing battle in technology to simultaneously make devices more effective (natural motions), yet also less complex and cumbersome. This often results in changes to the overall cosmetics of the device which can deter individuals by increasing the donning and doffing times of these prostheses. Lastly, as neuroprosthesis technology is a relatively new field, data on long-term reliability is not yet available, even simple systems for powered tenodesis grip for individuals with lesions at C6 or lower have not been fully explored in deference to volitional tendon transfer surgery (Popovic et al. 2002; Triolo et al., 1996).

**Table 24 Neuroprostheses**

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<thead>
<tr>
<th>Author Year Country</th>
<th>Research Design Score Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
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<tbody>
<tr>
<td>Ferrante et al. 2014 Italy Post Test N=14</td>
<td><strong>Population:</strong> Mean age: 47.9 yr; Gender: males=11, females=3; Injury etiology: SCI=8, Friedreich Ataxia=3, Amyotrophic Lateral Sclerosis=2, Multiple Sclerosis=1.</td>
<td>1. Grasping and reaching performance for all patients across all four tasks were rated by three observers with a</td>
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<td>Author Year</td>
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<td>Research Design</td>
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<tr>
<td>Kang 2013</td>
<td>South Korea</td>
<td>Observational</td>
<td>N=24</td>
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<tr>
<td>Scott &amp; Vare 2015</td>
<td>Australia</td>
<td>Post Test</td>
<td>N=16</td>
</tr>
<tr>
<td>Scott &amp; Vare 2015</td>
<td>Australia</td>
<td>Post Test</td>
<td>N=16</td>
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</table>
were 10 targets split between the trials, some of which had different locations or sizes compared to each other. Additionally, the speed of the virtual hand was altered in four speed increments progressively throughout the experiment with a low of speed 1 (18 on-screen units/s) to a high of speed 4 (196 on-screen units/s).

**Outcome Measures:** Absolute performance on task matching (time to complete (TTC)), Efficacy of completion on task matching (integral of the error (IOE)), Ability to issue appropriate commands using the virtual hand (percentage of errors (POE)).

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<tr>
<td>were 10 targets split between the trials, some of which had different locations or sizes compared to each other. Additionally, the speed of the virtual hand was altered in four speed increments progressively throughout the experiment with a low of speed 1 (18 on-screen units/s) to a high of speed 4 (196 on-screen units/s).</td>
<td>4. Non-injured participants had a significantly lower POE than those with SCI in completing Targets 3 and 4 (p&lt;0.05). 5. On examination of TTC, IOE and POE for Targets 5 and 6, no significant differences were found between SCI and non-injured participants (p&gt;0.05). 6. There was a significant increase in the TTC for Target 8 for SCI participants over non-injured participants (p&lt;0.05). 7. There was a significant increase in IOE for Target 7 by SCI participants when compared to non-injured participants (p&lt;0.05). 8. There was a significant increase in the POE commands for Target 7 and Target 8 for SCI participants compared to controls (p&lt;0.05). 9. Non-injured participants were significantly faster than SCI participants in completing Target 10 (p&lt;0.05), but there was no significant difference between the two groups for Target 9 (p&gt;0.05). 10. For speeds 1, 2, and 3, TTC scores were significantly lower for SCI participants (p&lt;0.05). 11. For IOE scores, non-injured participants had higher scores at speeds 1 and 3 compared to SCI participants (p&lt;0.05). 12. For POE scores, non-injured participants were scored significantly lower than the SCI participants at all four speeds (p&lt;0.05).</td>
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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 depend on length of time and the amount of assistance required to don and doff the device, 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 considering 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 controlled, eliminating an external coil and control unit.

Conclusion
There is level 4 evidence (from two post-tests; Ferrante et al., 2014; Scott and Vare, 2015) that although neuroprosthesis use increases functionality, patients score the device lower when looking at social factors such as comfort, encumbrance, and computer anxiety. Compared to healthy controls, patients with SCI encounter more challenges and slower times to use the device.

There is level 5 evidence (from one observational study; Kang, 2013) that pinch force can be increased with the use of an orthosis, and with greater efficiency.

The use of neuroprostheses appears to have a positive impact on pinch and grip strength and ADL functions in C5-C6 complete tetraplegia, however psychosocial factors continue to represent an obstacle in patient use.

9.1 Surface or Percutaneous Neuroprosthesis Systems

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 those with C5 and C6 level tetraplegia. The Freehand system can stimulate eight different muscles in order to produce a useful grip and key pinch in individuals with tetraplegia. 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 epimyseal 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 25 Freehand System

<table>
<thead>
<tr>
<th>Author Year</th>
<th>Country</th>
<th>Research Design</th>
<th>Score</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
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</table>
| Mulcahey et al., 2004 | USA | Case Series | N=4 | Population: Age: 13-16 yr; Level of injury: tetraplegia; Time since injury: 4-16 wk.  
Intervention: The following muscles were 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 Activities of Daily Living (ADL), Satisfaction with + without the Freehand System (Canadian Occupational Performance Measure (COPM)), Upper Extremity Capacity, Quadriplegic Index of Function. | 1. No statistical results are reported.  
2. No perioperative complications reported.  
3. Subjects began Freehand System use between 2-5 days after implantation.  
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.  
Intervention: Epimysial or intramuscular electrodes were implanted on the triceps. Following surgery standard stimulation exercise regimens were followed.  
Outcome Measures: 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). | 1. Variation in elbow moment across subjects significantly greater than the variance within subjects (ANOVA p<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 (30º flexion) and peaked with elbow at 90º flexion, significant ANOVA p<0.001.  
3. Elbow moment generated by triceps stimulation at 90º and 120º elbow flexion was significantly greater than elbow moment produced by tendon transfer (ANOVA p<0.05), no difference between elbow extension methods at 30º elbow flexion. |
Taylor et al., 2002
UK
Case Series
N=9

<table>
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<tr>
<th>Author Year Country</th>
<th>Research Design Score</th>
<th>Methods</th>
<th>Outcome</th>
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<tr>
<td>4.</td>
<td>Triceps stimulation and posterior deltoid together provided a greater elbow moment than each method separately, difference significant at each elbow position p&lt;0.05, except at 90º.</td>
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<td>5.</td>
<td>Quantitative workspace assessment done on 5 arms, more successful with triceps stimulation, significant for each subject, chi square p&lt;0.05.</td>
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<td>6.</td>
<td>Average acquisition time with triceps stimulation less than without stimulation 4/5 arms (3.2-6.4 seconds) and significant in 3/5 arms (unpaired t-test p&lt;0.01) and not for one p=0.076.</td>
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Population: Mean age: 38.4 yr; Gender: males=7, females=1; Level of injury: C4-C6; Mean time since injury: 10.1 yr.

Intervention: Assessment of the Freehand System.

Outcome Measures: Grasp Release Test, Grip Strength, Activities of Daily Living (ADL), Sensory ability (static 2 pt discrimination).

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-yr post implantation the types of tasks performed was 5.5 p=0.027, without the system it was 1.2 (p=0.028).
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).
4. At one-yr number of repetitions was increase to 50.5, p=0.046 with the system and without 24.3, p=0.28.

Hobby et al., 2001
UK
Pre-post
N=9


Intervention: 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, Activities of Daily Living (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.

Peckham et al., 2001
USA
Pre-post
N_initial=51; N_final=50

Participants: Age: 16-57 yr; Gender: males=42, females=9; Level of injury: C5-C6; Mean time since injury: 4.6 yr.

Intervention: Participants were trained to use the neuroprosthesis and to use it for 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.

Outcome Measures: Pinch strength, active ROM, Grasp-Release Test, Activities of Daily Living (ADL) Abilities Test, ADL Assessment Test & user satisfaction survey.

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).
2. 98% of participants moved at least one object with the neuroprosthesis (p<0.001) and 37 improved by moving at least three more objects (p<0.001). Disability was reduced in 49 of 50 participants as measured by the ADL abilities or ADL assessment tools.
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<th>Author Year</th>
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<th>Research Design</th>
<th>Score</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
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</table>
| Taylor et al., 2001             | UK      | Pre-Post        |       | N<sub>Initial</sub>=9; N<sub>Final</sub>=8 | Population: Age: 31-48 yr; Gender: males=7, females=1; Level of injury: C4-6; Time since injury=43-430 mo; Follow-up time=8-53 mo.  
Intervention: Interviews- reviewing use of Neuro Control Freehand System.  
Outcome Measures: Amount of Care & The System. | 1. No statistical results reported  
2. Completion of personal care was provided by outside nursing agencies. (mean 11.5 hr/day, range 3-24 hr); four users had additional care from family members (mean 3.4 hr/day, range 2-5 hr); no users claimed that care given by family members had decreased  
System-donning external components 5-10 min; most users reported no significant problems fitting the external equipment; two users had problems locating the coil; three locating the shoulder controller; one had persistent problems maintaining the position through the day due to the adhesive tape used becoming detached (four reported this as an occasional problem); four users had problems with skin allergy to the tape or double sided adhesive rings; two users reported that the system made transfers more difficult; three users never stopped using the system due to system failure; some problems with equipment reliability; no change in paid caregiver time; six users felt more confident when using the system; seven felt their quality of life had improved. |
Intervention: Participants were implanted with an upper extremity neuroprosthesis including a triceps’ electrode to provide stimulated elbow extension. Participants exercised triceps 4-6 hr/session using a programmed electrical stimulation exercise regimen that includes breaks. Participants exercised either nightly or every other night-whatever was best for maintaining an optimal amount of strength.  
Outcome Measures: Five overhead reaching tasks, Amount of assistance required to complete the task, Survey of home use. | 1. No statistical analysis was complete.  
2. Passive elbow extension was within normal limits.  
3. With stimulated triceps subjects attained full elbow extension; without it full range was not met. |
| 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.  
Intervention: The Freehand System – an implanted multichannel neuroprosthesis. | 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 post-surgery. |
Outcome Measures: Pinch forces, Grasp and Release Test (GRT), Activities of Daily Living (ADL) Test.

3. With neuroprosthesis, subjects could grasp, move and release more items in the 30 sec 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. After study, 5/6 subjects still used neuroprosthesis daily.

Population: Age: 13-53 yr; Gender: males=26, females=8; Level of injury: tetraplegia; Follow-up time: 1 yr.

Intervention: Implemented with a hand neuroprosthesis that provides grasp and release.

Outcome Measures: Standardized test of grasp and release (GRT), Measurements of pinch strength and range of motion, Satisfaction survey, Activities of Daily Living (ADL) survey.

1. 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, & 77% would pay for the neuroprosthesis if they had the money.

2. 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.

3. 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.

4. Occupation: 57% of responses to occupation questions were positive

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

6. Usage: used prosthesis median of 5.5 days/wk - ranged from 15 participants (44%) who donned the
<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Country</th>
<th>Research Design</th>
<th>Score</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kilgore et al., 1997</td>
<td>USA</td>
<td>Case Series</td>
<td>N=5</td>
<td></td>
<td></td>
<td><strong>Population:</strong> Age: 28-57 yr; Level of injury: C5-C6; Severity of injury: complete; Time since injury: 2-9 yr. <strong>Intervention:</strong> Implanted neuroprosthesis. <strong>Outcome Measures:</strong> Grasp force, Grasp-Release Test, Tests of Activities of Daily Living (ADL) (functional independence), Usage Survey.</td>
<td>neuroprosthesis 7 day/wk to five participants (15%) who used it less than one day/wk; 24/34 participants (71%) used it ≥4 day/wk; range of usage C4/C5, C5/C5, C6/C6 levels was the same (0-7 day/wk) C5/C6 group - used it most regularly 4-7 day/wk 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.</td>
</tr>
<tr>
<td>Mulcahey et al., 1997</td>
<td>USA</td>
<td>Pre-post</td>
<td>N=5</td>
<td></td>
<td></td>
<td><strong>Population:</strong> Age: 16-18 yr; Level of injury: C6=5, Time since injury: &gt;1yr. <strong>Intervention:</strong> Surgery. <strong>Outcome Measures:</strong> Grasp Release Test, Activities of Daily Living (ADL).</td>
<td>1. Pinch force ranged from 8 to 25N, with stimulation and greater than tenodesis grasp alone. 2. All demonstrated functional grasp patterns and were able to manipulate at least three more objects with the neuroprosthesis; had increased independence and were able to use the neuroprosthesis at home on a regular basis; the implanted stimulator proved to be safe and reliable.</td>
</tr>
<tr>
<td>Smith et al., 1996</td>
<td>USA</td>
<td>Case Series</td>
<td>N=5</td>
<td></td>
<td></td>
<td><strong>Population:</strong> Age: 13-19 yr; Gender: males=3, females=2; Level of injury: C5=5; Time since injury: 3-72 mo. <strong>Intervention:</strong> FNS versus Tenodesis. <strong>Outcome Measures:</strong> CWRU Hand System (Case Western Reserve University), Grasp and Release Test.</td>
<td>1. FNS versus Tenodesis 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). 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</td>
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<td>Author Year Country Research Design Score Total Sample Size</td>
<td>Methods</td>
<td>Outcome</td>
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<tr>
<td>Smith et al., 1994 USA Case Series N=5</td>
<td>Population: Age: 13-19 yr; Gender: males=5; Level of injury: C5-C6; Time since injury: 3-72 mo. Intervention: Intramuscular electrodes were implanted in the upper extremity muscles. Outcome measures: The Breslow Test.</td>
<td>palmar grasp forces increases from 2.1N (SD:2.9) to 11.1N (SD:6.0).</td>
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<tr>
<td></td>
<td>1. No predicted difference between electrodes in intrinsic and extrinsic muscles (p=0.93). 2. Significant differences were predicted between exit sites (p=0.016) + across muscle groups (p=0.047). 3. Survival likelihoods poorer for electrodes exiting dorsally. 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>
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Table 26 Summary Implanted Neuroprostheses (Freehand System and CWRU)

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<thead>
<tr>
<th>Author Year Country Research Design Score Total Sample Size</th>
<th>Methods</th>
<th>Main Outcome(s)</th>
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<tbody>
<tr>
<td>Author Year Country Research Design Score Total Sample Size</td>
<td>Methods</td>
<td>Main Outcome(s)</td>
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<tr>
<td>Author Year Country Research Design Score Total Sample Size</td>
<td>Methods</td>
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<td>Author Year Country Research Design Score Total Sample Size</td>
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<td>Author Year Country Research Design Score Total Sample Size</td>
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<td>Main Outcome(s)</td>
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<td>Author Year Country Research Design Score Total Sample Size</td>
<td>Methods</td>
<td>Main Outcome(s)</td>
</tr>
</tbody>
</table>
### Table

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

### Discussion

Although Freehand System results in significant positive functional outcomes for individuals with tetraplegia, the unavailability of the device impacts its clinical use greatly. Some devices are still available on a selective basis (Cornwall & Hausman, 2004; Ragnarsson, 2008), however there is no opportunity for standardized clinical use at this time. Additionally, most patients need to undergo multiple surgeries for the implantation of electrodes and other various components of the device in order to gain optimal use of the system. This represents another barrier to the wide spread application of the Freehand System.

### Conclusion

*There is level 4 evidence (from eight case series; Malcahey et al., 2004; Memberg et al., 2003; Taylor et al., 2002; Bryden et al., 2000; Wuolle et al., 1999; Kilgore et al., 1997; Smith et al., 1994; Smith et al., 1996) that the implanted Freehand System increases grip strength, grasping, ADL and function, and overall independence.*

*There is level 4 evidence (from five pre-post studies; Peckham et al., 2001; Taylor et al., 2001; Hobbey et al., 2001; Carroll et al., 2000; Mulcahey et al., 1997) that the implanted Freehand System results in positive increases in grip strength, grasping and overall independence.*
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; Venugopalan et al., 2015). It has been FDA approved for use with individuals with stroke and SCI. 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 tetraplegia 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 digitorum 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 the rigid arm splint which does not provide enough flexibility 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 27 NESS H200 (formerly Handmaster-NMS-1)

<table>
<thead>
<tr>
<th>Author &amp; McBride 2003 USA Pre-Post N=7</th>
<th>Population: Gender: males=7, females=0; Level of injury: C5-C6; Mean time since injury: 6 mo.</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intervention: Subjects practiced with the neuroprothesis daily to regain grasp, hold, and release ability and to restore selected functions of 1 of the 2 paralyzed hands. Subjects were observed 2-3x/wk for 3 wks.</td>
<td>1. All were 100% successful in using the handmaster in the studied ADL and grasp (hold and release) tasks. 2. Improvements were noted in strength (0.57±98N to 16.5±4.4N, finger linear motion (0.0cm to 8.4±3.2cm) and Fugi-Meyer scores (p&lt;0.05).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Snoek et al., 2000 Netherlands Pre-Post N&lt;sub&gt;Initial&lt;/sub&gt;=10; N&lt;sub&gt;Final&lt;/sub&gt;=4</th>
<th>Population: Age: 20-65 yr; Gender: males=8, females=2; Level of injury: C4 to C6; Classification: 3-Cu=3, 1-O=5, 2-O=1, 0-O=1; Fitted hand: Right n=6, Left n=4.</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1. Six people left the study for various reasons (&gt;50%). Over all the four remaining were able to perform several tasks with the Handmaster that they were not able to without it (i.e., 3/4 were able to put the splint on independently).</td>
</tr>
</tbody>
</table>

### Table 28 Summary NESS H200 (formerly Handmaster-NMS-1)

<table>
<thead>
<tr>
<th>Author &amp; McBride 2003</th>
<th>N</th>
<th>Intervention</th>
<th>Main Outcome(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>NESS Handmaster</td>
<td>+ve ADL use +ve Grasp Release Test</td>
<td></td>
</tr>
</tbody>
</table>
### Conclusion

*There is level 4 evidence (from two pre-post studies; Alon and McBride, 2003; Snoek et al., 2000) that with sufficient practice using the NESS H200 is a reliable way to regain grasp, hold and release abilities in tetraplegic patients.*

The NESS H200 represents a reliable non-invasive alternative for individuals with tetraplegia with the goal of regaining some functional grasping abilities.

### 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 29 Bionic Glove

<table>
<thead>
<tr>
<th>Author Year</th>
<th>Country</th>
<th>Research Design</th>
<th>Score</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Popovic et al., 1999</td>
<td>Yugoslavia</td>
<td>Case Series</td>
<td>N=12</td>
<td></td>
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</tbody>
</table>

**Population:** Mean age: 26.5 yr; Level of injury: C5-C7; Severity of injury: complete=10, incomplete=12; Length of experience with device: ≥6 mo.

**Intervention:** Taught how to use the device.

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 six mo. When three clients excluded who had 120 points on FIM scores were beginning...
**Table 30 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>
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<td></td>
<td></td>
<td></td>
<td>+ve compliance (60%)</td>
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</tbody>
</table>

**Conclusion**

*There is level 4 evidence (from two case series; Popovic et al., 1999; Prochazka et al., 1997) that the Bionic Glove can provide an increase in upper limb functioning and motor function.*

The Bionic Glove can be successfully used in SCI patients who still have voluntary control over the wrist to enhance tenodesis grasp.
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 four 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 disadvantages that include a lengthy time to don and doff the device (seven to ten 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 advantages in this system is that it is easily programmable (Popovic et al., 2006).

Table 31 ETHZ ParaCare and Compex Motion Systems

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Country</th>
<th>Research Design</th>
<th>Score</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mangold et al.,</td>
<td>2005</td>
<td>Switzerland</td>
<td>Case Series</td>
<td>N=11</td>
<td></td>
<td>Population: Age: 15-70 yr; Gender: males=9, females=2; Level of injury: C5-C7; Severity of injury: AIS A-D.</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.</td>
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<td></td>
<td>Intervention: FES was carried out with a stationary stimulation system and two portable systems (ETHZ-Paracare FES system, and Complex Motion).</td>
<td>2. Surface FES system is more flexible in its application and does not need surgical procedures.</td>
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<td></td>
<td>Outcome Measures: Videos of functional tasks: hand function tests, Self-designed functional tests, Follow-up query-assessment of muscle strength.</td>
<td>3. High flexibility in electrode placement, stimulation programmes, and FES control devices is required in order to adapt the system to individual needs.</td>
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</tbody>
</table>

Table 32 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>
<tbody>
<tr>
<td>Mangold et al.,</td>
<td>11</td>
<td>ETHZ-ParaCare FES System and Compex Motion</td>
<td>+ve Training Programme</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+ve Functional exercises in therapy</td>
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<td></td>
<td></td>
<td></td>
<td>=ADL function in rehab centre</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>-ve ADL use at home</td>
</tr>
</tbody>
</table>

Conclusion

"There is level 4 evidence (from one case series; Mangold et al., 2005) that the ETHZ-ParaCare System represents a specific niche in flexible neuroprosthesis options as the placement of the electrodes is flexible (non-surgical) and has"
shown positive outcomes in rehabilitation and the ability to perform daily living tasks.

The ETHZ-ParaCare System is not yet commercially available and therefore does not represent a current option for the majority of patients with SCI. However, future models should be considered if commercially available.

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.

9.1.6 Exo-Glove

The Exo-Glove is a soft, wearable, lightweight, hand robot that uses soft tendon routing system and an underactuation mechanism (It et al., 2015). The Exo-Glove has been tested among healthy subjects and in one participant suffering from paralysis of the hand secondary to SCI. The use of the glove was reported to have aided in grasping various objects among the individual with SCI (It et al., 2015). Other devices for use among SCI injured individuals that have been tested within larger research studies are presented below.

Table 33 Other Surface or Percutaneous Neuroprosthesis Systems
<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>
| Backus et al. 2014 | USA    | Pre-Post | N=18         |                   | **Population:** Mean age: 40.5±13.0 yr; Gender: males=8, females=2; Level of injury: C2-C3=3, C4-C7=7; Mean ASIA motor score: 15.8±3.9; Mean time since injury: 3.0±1.1 yr.  
**Intervention:** Test effect of assisted movement with enhanced sensation (AMES) using vibration to antagonist muscle to reduce impairments and restore upper limb function in people with incomplete tetraplegia. Two or three sessions over 9-13 wk per participant.  
**Outcome Measures:** Strength and active motion tests on the AMES device, International Standards for the Neurological Classification of SCI (ISNCSCI) motor and sensory examinations, Modified Ashworth Scale (MAS), grasp and release test (GRT), Van Lieshout Test (VLT), Capabilities of Upper Extremity questionnaire (CUE). | 1. No significant change in MAS scores (p=0.371) or ISNCSCI scores (p=0.299 for motor, p=0.459 for sensory-light tough, p=0.343 for sensory-pin prick).  
2. Strength test scores increased significantly for MCP extension (p≤0.01) and flexion (p≤0.05) and for wrist extension (p≤0.001) and flexion (p≤0.01).  
3. Active motion test scores increased significantly for MCP joints (p≤0.001) and wrist (p≤0.001).  
4. Out of GRT, VLT and CUE scores, only GRT scores were significantly improved after training and slightly between posttreatment and 3-mo post treatment (p=0.025). |
| Coignard et al. 2013 | France | Observational | N=63       |                   | **Population:** *Injury Group (n=29)*: Mean age=37.8±13.3 yr; Injury etiology: spinal cord=23, post-stroke locked in syndrome=2, arthrogryposis=1, quadruple amputee=1, cerebral palsy=1, spinal muscular atrophy=1; *Controls (n=34)*: Mean age=32.4±11.2 yr.  
**Intervention:** No intervention. To evaluate the reliability and functional acceptability of the “Synthetic Autonomous Majordomo” (SAM) robotic aid system in a domestic environment using three multi-step scenarios: selection of the room in which the object to be retrieved was located, selection of the object to be retrieved, the grasping of the object itself and the robot’s return to the user with the object.  
**Outcome Measures:** Selection time (time between task’s “start” command and room/object selection click), Number of failures, Qualitative questionnaire. | 1. No significant difference between scenarios 1 and 2 in room/object selection, validation times and number of failures for controls and patients (p>0.05).  
2. Statistically significant difference between scenario 2 and 3 in object selection time for controls and patients (p<0.05) but not for number of object selection failures (p>0.05).  
3. Patients took significantly longer to select the room and the object than the controls did (for room selection in scenarios 1 and 3 and for object selection in all three scenarios) (p<0.05).  
4. No significant patient vs. control differences in the number of failures (p>0.05).  
5. Experience of computer use had significantly affected speed of task for patients in scenario 3 (p<0.05) and controls in all scenarios (p<0.05).  
6. Overall, the robot was found to be acceptable by both patients and control participants. |
**Population:** Mean age: 44.8±16.3 yr; Gender: males=8, females=2; Level of injury: C4-C6=10; Severity of injury: AIS-A complete=3, AIS-B incomplete=4, AIS-C incomplete=1, AIS-D incomplete=2; Mean time since injury: 4.7±2.5 yr.

**Intervention:** Chronic tetraplegic SCI patients participated in a 6-wk wrist-robot training protocol (1hr/day, 3 times/wk) to evaluate feasibility, safety and effectiveness on upper limb.

**Outcome Measures:** Motor performance, Corticospinal excitability, Upper extremity Motor score (UEMS), Visual Analogue Scale (VAS), Modified Ashworth Scale (MAS), resting motor threshold (RMT), Motor evoked potential (MEP) amplitude and latency at rest, MEP facilitation.

<p>| | |</p>
<table>
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<tbody>
<tr>
<td>1.</td>
<td>Significant improvements in aim and smoothness (p=0.03).</td>
</tr>
<tr>
<td>2.</td>
<td>No changes in deviation, mean speed, peak speed and duration of movement was found.</td>
</tr>
<tr>
<td>3.</td>
<td>No changes in motor strength of trained right arm (p=0.4) or untrained left arm (p=0.41).</td>
</tr>
<tr>
<td>4.</td>
<td>No significant changes in MAS of either arm (p=0.05 for both).</td>
</tr>
<tr>
<td>5.</td>
<td>No significant changes in pain levels after training (p=0.99).</td>
</tr>
<tr>
<td>6.</td>
<td>There were no changes in any neurophysiological parameters after the 6-wks of training (p&gt;0.05).</td>
</tr>
<tr>
<td>7.</td>
<td>Strong positive correlation between change in smoothness according to the initial spasticity level ($R^2=0.403$); change in aim was positively correlated with initial spasticity in trained arm ($R^2=0.123$).</td>
</tr>
<tr>
<td>8.</td>
<td>Initial UEMS and MEP amplitude had no correlation with the change on smoothness and aim.</td>
</tr>
</tbody>
</table>

**Conclusion**

*There is level 4 evidence (from two pre-post studies; Backus et al., 2014; Cortes et al., 2013) that the Exo-Glove can be safely used in patients with tetraplegia to significantly improve upper limb effectiveness.*

*There is level 5 evidence (from one observational study; Coignard et al., 2013) that in a real-world home environment the functionality of the Exo-Glove may be limited, and that healthy controls still exhibit greater control over the robotic device than those with SCI.*

The Exo-Glove is a non-invasive safe option for SCI and tetraplegic patients, although the real-world functionality of it may be limited and can be hard to use based on individual functioning.

### 9.1.7 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.

### 9.1.8 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 (two 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 inputs.
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).

9.1.9 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 aperature 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 Myoelectrically Controlled Neuroprostheses

Second generation neuroprosthesis 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 (two to four 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 bench testing, is worn on the wrist and wirelessly communicates with the implantable stimulator (Wheeler & Peckham 2009).

### Table 34 Second Generation Neuroprosthesis: Myoelectrically Controlled

<table>
<thead>
<tr>
<th>Author Year</th>
<th>Country</th>
<th>Research Design</th>
<th>Score</th>
<th>Total Sample Size</th>
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<tbody>
<tr>
<td>Kilgore et al., 2008</td>
<td>USA</td>
<td>Pre-post</td>
<td>N=3</td>
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<tr>
<th>Methods</th>
<th>Outcome</th>
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<tr>
<td>Population: Mean age: 34.0±9.5 yr; Level of injury: C5=1, C6=2.</td>
<td>1. Functional Outcomes: all three subjects used their NP to perform activities that they could not perform prior to implantation (post implant follow up ranged from 2-4 yr).</td>
</tr>
<tr>
<td>Intervention: A second generation neuroprosthesis system was implanted into individuals and functional outcomes were evaluated.</td>
<td>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=0.038).</td>
</tr>
<tr>
<td>Outcome Measures: Grasp and Release Test (GRT), Activities of Daily Living Abilities (ADLAT), Craig Handicapped Assessment and Reporting Tool (CHART), NP Usage Survey.</td>
<td>3. Activities: every subject was able to double the number of objects manipulated in the GRT with NP (two subjects completed 6/6 tasks; one subject 5/6 tasks)</td>
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<td>4. ADLAT all three subjects improved in least five activities with one subject in all nine.</td>
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<td></td>
<td>5. Participation: all three subjects increased their scores for physical independence, one in the mobility task, one in the social integration scale, one subject a decrease in occupation subscale.</td>
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<td></td>
<td>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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</table>

### Discussion

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 eight 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%.

Thorsen et al. (2013) tested the myoelectrically controlled FES (MeCFES). 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. Participants received occupational therapy with and without the MeCFES. Immediate improvements were found in upper limb functioning with the use of the MeCFES and these improvements were maintained post-treatment (Thorsen 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; Vanmulken et al., 2015). Feasibility studies suggest that robot–assisted technology may be easy to learn and perform, yet, further research is necessary to determine the potential for improving upper limb functioning, and when rehabilitation using robot-assisted technologies may be most beneficial (Vanmulken et al., 2015).

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.*

*There is level 4 evidence (from one pre-post study; Thorsen et al., 2013) that the use of the MeCFES, a second generation neuroprosthesis, in combination with occupational therapy improved tenodesis grip in people with tetraplegia.*

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.

The MeCFES neuroprosthesis, a second generation, myoelectrically controlled FES device appears to have a positive effect on tenodesis grip.

10.0 Brain Interface Neuroprostheses

11.0 Virtual Reality

12.0 Summary

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 there are fewer studies than may be expected 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 1b evidence (from one randomized controlled trial; Rice et al., 2014) that education improves wheelchair skills after 1- year post discharge.

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, and is correlated to a decrease in stress, pain, and depression.

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 overall muscle strength continues to improve up to 15 months’ post hospital discharge for both persons with tetraplegia and paraplegia despite large variability in patients.

There is level 5 evidence (from one observational study; Bunday et al., 2014) that the control of precision grip involves premotoneuronal subcortical mechanisms, which are lacking after SCI.
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 2 evidence (from two randomized control trials; Klose et al., 1990; Klose et al., 1993) that the addition of biofeedback does not improve patient scores in rehabilitation more than physical exercise alone.

There is level 4 evidence (from one pre-post test; Bruker and Bulaeva, 1996) that EMG biofeedback sessions can significantly improve normal EMG muscle test scores of both triceps.

There is level 4 evidence (from one post-test; Foldes et al., 2015) that patients with complete hand paralysis can learn to significantly modulate their sensory motor rhythms using a virtual hand task over time.

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 4 evidence (from two pre-post studies; Di Rienzo et al., 2014b, 2015) that MI treatment incorporated into physiotherapy for individuals with SCI may help to improve prehensile tenodesis performance.

There is level 1a evidence (from three randomized controlled trials; Bekkhuizen & Field-Fote 2005, 2008; Hoffman & Field-Fote 2013) 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 1b evidence (from one randomized control trial; Gomes-Osman & Field-Fote, 2014) that showed that rTMs treatment in individuals with chronic stable SCI 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; Gomes-Osman & Field-Fote, 2015) that showed that tDCS, TENS, and vibration therapy resulted in significant improvements in upper extremity function and pinch strength.

There is level 4 evidence (from one post-test study; Scandola et al., 2014) that showed that the induction of the rubber hand illusion through synchronous multisensory visuo-tactile bodily stimulation resulted in ownership of the hand.

There is level 4 evidence (from one pre-post study; Belci et al., 2004) that showed therapeutic TMS can lower intracortical inhibition, which is linked to better clinical motor scores.

There is level 4 evidence (from one pre-post study; Nasser et al., 2014) that showed massed practice and somatosensory stimulation significantly improved
motor function and pinch grip strength compared to traditional rehabilitation programs over time.

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 4 evidence (from one post-test study; Stahl et al., 2015) that among persons with chronic SCI motor planning for aperture modulation is preserved.

There is level 4 evidence (from one case series; Barbetta et al., 2016) that the presence of musculoskeletal pain is not necessarily related to lifestyle factors (such as BMI and mobility aid) but more of a function of other demographic factors (such as gender, age, and level of injury).

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 5 evidence (from one observational study; Akbar et al., 2014) that people with paraplegia are significantly more likely to develop bilateral carpel tunnel syndrome.

There is level 4 evidence (from two case series studies; House et al., 1992; Waters et al., 1985) that metacarpal fusion can increase pinch strength as well as improve the over all ability to complete daily living tasks.

There is level 4 evidence (from one pre-post study; McCarthy et al., 1997) that the addition of intrinsic balancing procedures to extrinsic hand reconstruction can improve pinch strength and the ability to perform daily living tasks compared to extrinsic hand reconstruction alone.
There is level 3 evidence (from one retrospective study; Forner-Cordero et al., 2003) that the outcomes of pinch and grasp reconstructive surgeries overall improve the individuals’ hand function and meet individual expectations.

There is level 4 evidence (from seven case studies; Meiners et al., 2002; Lo et al., 1998; Failla et al., 1990; Gansel et al., 1990; Rieser and Waters, 1986; Kelly et al., 1985; Colyer and Kappleman, 1981) that pinch and grasp reconstructive surgeries are effective in increasing motor function, strength, and grip of the hand. Patients are also report high satisfaction with their surgical results.

There is level 2 evidence (from one prospective control trial; Rabischong et al., 1993) that surgery can increase rotation in the elbow and the relationship with peak torque.

There is level 3 evidence (from one case-control; Dunkerley et al., 2000) that PD to triceps surgical intervention can have limited/similar results to controls when examining functional outcome.

There is level 4 evidence (from two case series; Lacey et al., 1986 and Raczka et al., 1984) that PD to triceps surgery can have a positive effect on functional use as well as result in positive patient satisfaction with surgery.

There is level 4 evidence (from one pre-post study; Remy-Neris et al., 2003) that restoring elbow extension is important for over all upper limb kinematics, however surgical interventions can have limited results.

There is level 2 evidence (from one RCT; Mulcahey et al., 2003) that biceps to triceps surgery can increase elbow extension strength, reaching, and overall performance improvement.

There is level 4 evidence (from two case series; Kozin et al., 2010; Kuz et al., 1999) that elbow extension surgery improves elbow extension and overall functionality of the joint.

There is level 4 evidence (from one pre-post study; Friden et al., 2012a) that multiple reconstructions can improve key-pin and grip strength.

There is level 3 evidence (from one case-control study; Friden et al., 2012b) that patients who had multiple stage BR to FPL through the intersosseous membrane had significantly greater active pronation, while other measures remained similar.

There is level 4 evidence (from nine case series; Rothwell et al., 2003; Welraeds et al., 2003; Freehafer, 1998; Mohammed et al., 1992; Ejeskar and Dahllof 1988; Freehafer et al., 1984; Lamb and Chan, 1983; Hentz et al., 1983; Friden et al., 2014) that multiple reconstructive surgery overall increases motor function as well as the ability to perform daily living tasks.
There is level 4 evidence (from one post-test; Gregersen et al., 2015) that a variety of reconstructive surgeries can be used to improve overall elbow function and strength.

There is level 2 evidence (from one cohort study; Dunn et al., 2004) that active transfer procedures may have little benefit over tenodesis procedures as the rate of decline post-surgery is greater and other functional outcomes are equal.

There are only a few 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 (from one case series; Fox et al., 2015a) that nerve transfer surgery can increase functionality and grasp strength in some patients, however not all patients have successful surgical outcomes.

There is level 2 evidence (from one cohort study; Fox et al., 2015b) that the risk of negative outcomes, such as postoperative decline compared to baseline, for nerve transfer surgery are low.

There is level 4 evidence (from one post-test study; Bertelli et al., 2015) that nerve transfer surgery can increase motor hand function without compromising donor site function in patients with midcervical spinal cord injuries.

There is level 4 evidence (from two post-tests; Ferrante et al., 2014; Scott and Vare, 2015) that although neuroprosthesis use increases functionality, patients score the device lower when looking at social factors such as comfort, encumbrance, and computer anxiety. Compared to healthy controls, patients with SCI encounter more challenges and slower times to use the device.

There is level 5 evidence (from one observational study; Kang, 2013) that pinch force can be increased with the use of an orthosis, and with greater efficiency

There is level 4 evidence (from eight case series; Malcahey et al., 2004; Memberg et al., 2003; Taylor et al., 2002; Bryden et al., 2000; Wuolle et al., 1999; Kilgore et al., 1997; Smith et al., 1994; Smith et al., 1996) that the implanted Freehand System increases grip strength, grasping, ADL and function, and overall independence.

There is level 4 evidence (from five pre-post studies; Peckham et al., 2001; Taylor et al., 2001; Hobbey et al., 2001; Carroll et al., 2000; Mulcahey et al., 1997) that the implanted Freehand System results in positive increases in grip strength, grasping and overall independence.
There is level 4 evidence (from two pre-post studies; Alon and McBride, 2003; Snoek et al., 2000) that with sufficient practice using the NESS H200 is a reliable way to regain grasp, hold and release abilities in tetraplegic patients.

There is level 4 evidence (from two case series; Popovic et al., 1999; Prochazka et al., 1997) that the Bionic Glove can provide an increase in upper limb functioning and motor function.

There is level 4 evidence (from one case series; Mangold et al., 2005) that the ETHZ-ParaCare System represents a specific niche in flexible neuroprosthesis options as the placement of the electrodes is flexible (non-surgical) and has shown positive outcomes in rehabilitation and the ability to perform daily living tasks.

There is level 4 evidence (from two pre-post studies; Backus et al., 2014; Cortes et al., 2013) that the Exo-Glove can be safely used in patients with tetraplegia to significantly improve upper limb effectiveness.

There is level 5 evidence (from one observational study; Coignard et al., 2013) that in a real-world home environment the functionality of the Exo-Glove may be limited, and that healthy controls still exhibit greater control over the robotic device than those with SCI.

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.

There is level 4 evidence (from one pre-post study; Thorsen et al., 2013) that the use of the MeCFES, a second generation neuroprosthesis, in combination with occupational therapy improved tenodesis grip in people with tetraplegia.
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