Upper Limb Rehabilitation Following Spinal Cord Injury

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Key Points

Physical rehabilitation increases muscle strength and function to improve hand task performance and quality of life in individuals with SCI.

Minimal clinical research evidence exists to support the use of orthoses in preventing joint problems or improving hand function.

Providing education to manual wheelchair users may be effective in improving wheelchair skills and preventing shoulder pain.

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

There is limited evidence to support the use of action-observation therapy in SCI rehabilitation.

Rehabilitation using virtual reality interventions produces similar results to conventional therapy and may help to improve hand function, as well as activities of daily living, through an engaging platform as a supplement to conventional therapy.

Upper extremity robotics improve hand function in individuals who have suffered upper limb paralysis following a spinal cord injury. However, further research is necessary to determine the efficacy of upper extremity robotic exoskeletons as part of a robotic rehabilitation program.

BCI technology as a rehabilitative therapy is feasible and may be efficacious in promoting neuroplasticity, however, further technological advancement is necessary to provide benefit as an assistive device in tasks related to daily living at home.

EMG biofeedback does not improve motor function of the upper extremity in SCI rehabilitation patients.

A variety of neuroprostheses exist that have demonstrated significant improvements in upper extremity function. As technology and surgical procedures advance, these systems may become more affordable and accessible for individuals with SCI.

There is mixed evidence about the efficacy of NMES to improve muscle strength.

When combined with TENS, functional task practice may improve aspects of hand-related function, however, more clinical trials to determine the long-term rehabilitative effects of TENS therapy are necessary.

The evidence is conflicting as to whether FES is effective alone or in combination with massed practice training.
More research is necessary to determine the efficacy of muscle vibration therapy in SCI rehabilitation.

rTMS has many applications and may improve functional outcomes alone or in combination with PNS and reconstructive surgery.

tDCS may provide some advantage in improving upper extremity muscle strength and hand grasp, however, larger clinical trials are necessary to determine the effectiveness of tDCS as a long-term rehabilitative therapy.

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

Surgical intervention for recovery of upper limb function significantly improves motor outcomes and the ability to perform ADLs.

A variety of diverse pinch and grasp reconstructive procedures improve hand function and QOL.

Deltoid-to-triceps surgery may improve motor function and the ability to perform daily living tasks, leading to surgical satisfaction.

Biceps-to-triceps elbow extension is a viable surgical option for those with limited function, impacting activities of daily living.

Multiple reconstructive surgeries help to improve pinch, grip, and elbow extension functions that improve ADL performance and QOL in tetraplegia.

Nerve transfer surgery to restore hand and upper limb function in SCI patients is a viable alternative to tendon transfer in acceptable candidates.

Acupuncture and Trager therapy may reduce upper limb pain post-SCI, however, there is limited evidence that acupuncture improves neurological and functional recovery in SCI.
# Table of Contents

Key Points ........................................................................................................................................................................i

1.0 Executive Summary .......................................................................................................................................................... 1

2.0 Introduction ......................................................................................................................................................................... 3

3.0 Therapy Based Interventions ............................................................................................................................................ 5
  3.1 Exercise & Strengthening .................................................................................................................................................. 5
  3.2 Orthoses .......................................................................................................................................................................... 10
  3.3 Skills Training and Education .......................................................................................................................................... 14
  3.4 Motor Imagery ................................................................................................................................................................. 17
  3.5 Action Observation ......................................................................................................................................................... 19

4.0 Technology Based Interventions ...................................................................................................................................... 20
  4.1 Virtual Reality ................................................................................................................................................................. 20
  4.2 Robotics .......................................................................................................................................................................... 26
  4.3 Brain Computer Interfaces .............................................................................................................................................. 32
  4.4 EMG Biofeedback ......................................................................................................................................................... 37
  4.5 Neuroprostheses ............................................................................................................................................................. 40

5.0 Sensorimotor Stimulation Interventions .......................................................................................................................... 49
  5.1 Neuromuscular Electrical Stimulation ............................................................................................................................. 49
  5.2 Transcutaneous Electrical Nerve Stimulation .................................................................................................................. 51
  5.3 Functional Electrical Stimulation .................................................................................................................................. 57
  5.4 Muscle Vibration ............................................................................................................................................................ 63

6.0 Non-Invasive Brain Stimulation Interventions ................................................................................................................. 66
  6.1 Repetitive Transcranial Magnetic Stimulation ................................................................................................................ 66
  6.2 Transcranial Direct Current Stimulation ......................................................................................................................... 70

7.0 Pharmacological Interventions ......................................................................................................................................... 73
  7.1 Baclofen ........................................................................................................................................................................... 73

8.0 Reconstructive Surgery and Tendon Transfers ................................................................................................................. 75
  8.1 Hand .................................................................................................................................................................................. 75
    8.1.1 Pinch ......................................................................................................................................................................... 76
    8.1.2 Pinch & Grasp .......................................................................................................................................................... 79
  8.2 Elbow Extension .............................................................................................................................................................. 84
    8.2.1 Posterior Deltoid to Triceps ....................................................................................................................................... 84
    8.2.2 Biceps to Triceps ....................................................................................................................................................... 87
8.3 Multiple Reconstructions ................................................................................................. 90
8.4 Nerve Transfers ............................................................................................................. 96
9.0 Complementary & Alternative Medicine ...................................................................... 101
10.0 Summary ..................................................................................................................... 104
Upper Limb Rehabilitation Following Spinal Cord Injury

1.0 Executive Summary
What functional impairments occur to the upper limbs following spinal cord injury?

SCI can result in complete or partial paralysis of the upper limbs depending on the level and completeness of the lesion. Sensory and autonomic deficits, as well as pain, are also important consequences of SCI that can impact upper extremity function. The use of the upper extremities is critical in completing basic activities of daily living, such as self-feeding, dressing, bathing and toileting. The upper extremities also play a significant role in mobility needs, as transfers, transitional movements, and wheeled mobility are completed using one’s arms (Snoek et al., 2004). The level of assistance required may range from completely caregiver dependent to partially functional in activities of daily living, social/recreational activities and work related activities (Yozbatiran & Francisco, 2019). Accordingly, restoration of upper limb function was rated above control of bladder and bowel function, spasticity, pain and sexual function in individuals that have experienced a SCI (Ward & Power, 2019).

What are the chances of recovering upper limb function following a spinal cord injury?

The level of function/independence recovered is influenced by completeness and level of injury (cervical vertebrae C4-C7). In complete SCI (AIS A), no neural transmission occurs below the point of injury (Courtine & Sofroniew, 2019). However, a motor level recovery of two or more levels is rare in those with cervical complete SCI; typically, a recovery of one level occurs (Courtine & Sofroniew 2019). In contrast, in incomplete spinal cord injuries (AIS B, C, D) some neural transmission can still pass through the spinal cord (Courtine & Sofroniew 2019).

The level of injury also plays an important role in determining the outcomes of functional recovery. The most detrimental outcomes are observed if C4 is affected (Nas et al., 2015). At this level of injury, a patent will be able to manage their respiration but will otherwise be completely dependent (Nas et al., 2015). If C5 is affected, the patient will have a better prognosis as they may have active elbow flexion but will still need assistance with ADLs (Nas et al., 2015). Improvements in functional independence are often associated with injury to level C6 or C7 (Nas et al., 2015). Injury to C6 allows for active wrist extensions and a hand grip may be achieved with tenodesis (Nas et al., 2015). This allows for an individual to be independent in activities like nutrition, self-care and hygiene (Nas et al., 2015). Furthermore, injury to C7 allows active elbow extension in addition to active wrist extension (Nas et al., 2015). Therefore, individuals with this injury are capable of transferring successfully in a wheelchair and may have increased independence (Nas et al., 2015).

What management options are there for upper limb functional impairments after spinal cord injury?

Some standardized rehabilitation procedures have been established, however, there is no consensus on the most effective therapeutic options. However, the treatment approach is dependent on the severity/level of injury and the client’s goals for rehabilitation.
Non-Pharmacological Options

- Therapy based interventions
- Sensorimotor stimulation interventions
- Surgical interventions
- Technology based interventions
- Non-invasive brain stimulation interventions
- Complimentary and alternative medicine

Pharmacological Options

- Baclofen
- Neuromuscular modulator

Taken together, the severity of the lesion dictates the treatment approach and the goals of rehabilitation, which are summarized below.

Adapted from Dietz & Fouad, 2013.
Gaps in the Evidence

- Further research is necessary to directly compare the efficacy of each exercise/strength training program to each other. In addition, Haisma et al. (2006) and Sipski and Richards (2006) recommended further research in a variety of areas including optimal methods for strengthening muscles, merits of endurance versus strength training, and ROM, ADL, and transfer training.
- Research should focus on determining the efficacy of orthoses as rehabilitative or assistive devices, as well as the type and duration of splint necessary for different levels/severities of SCI.
- Continued research should focus on: (1) comparing virtual reality systems to conventional therapy with randomized controlled trials in a larger population, (2) development of telerehabilitation programs to complement virtual reality intervention, and (3) efficacy of virtual reality systems and types of exercises included.
- Future research should focus on determining effective electrical stimulation patterns.

2.0 Introduction
Raineteau and Schwab (2001) define 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.

The level at which the injury or lesion occurs and the completeness of the lesion (incomplete or complete) dictate the level of independence of the affected individual (Ditunno 1999). If a SCI occurs above or within the cervical levels (C1 – C8), upper and lower extremity motor and/or sensory function is affected (Witiw and Fehlings 2015). In contrast, if a SCI occurs between T1 – L5, upper extremity function is preserved, while lower extremity motor/sensory function is impaired (Witiw and Fehlings 2015). It is estimated that cervical SCI accounts for approximately 50% of all people living with SCI (Steeves et al., 2007).

Level of function/independence is also influenced by completeness of the lesion. In complete spinal cord injuries, no neural transmission occurs below the point of injury, resulting in a complete loss of function below the point of injury (Courtine & Sofroniew 2019). In contrast, some neural transmission can still pass through the spinal cord in incomplete lesions. (Courtine & Sofroniew 2019).

The World Health Organization estimates that between 250 000 and 500 000 people experience a SCI each year (WHO, 2013). Due to advances in surgical procedures, supportive measures and rehabilitation protocols, functional outcomes have improved and the rate of morbidity has decreased (Ahuja et al., 2017). However, many functional deficits remain and individuals experience permanent disabilities (Anderson, 2004; Courtine et al., 2019). The loss of upper extremity 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 also requires significant upper extremity function, such as transfers from surface to surface, transitional movements such as rolling, bridging and sit to lie, crutch walking and wheeled mobility (Snoek et al. 2004).
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 (and 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).

To lessen the impact of negative functional outcomes in motor recovery, functional independence, social integration and quality of life in individuals with SCI, clinical practice guidelines were developed by the Paralyzed Veterans Association (Consortium for Spinal Cord Medicine 2005). These guidelines outline the expected skills/outcomes that should be achieved at each significant level of injury and help guide physicians in the management of primary and secondary complications (Consortium for Spinal Cord Medicine 2005). Secondary complications from SCI present ongoing challenges for upper extremity function and include pain, spasticity, contractures and upper limb musculoskeletal injuries (Sipski & Richards 2006).

The initial care, management, rehabilitation, and prevention of injuries in the upper limb of those with tetraplegia is of great importance in maximizing and maintaining independence. However, management of the tetraplegic upper limb tends to be eclectic, involving functional strength training (repetition-heavy movements of ADL), orthoses and upper extremity surgery. Typically, treatment of upper extremity loss of function follows a stepwise approach, with conservative treatment methods applied first, followed by functional electrical stimulation and surgical interventions (Bryden et al., 2005). In addition, treatment of the upper limb is often divided into three phases: acute, subacute and reconstruction (Murphy and Chuinard 1998). The aims of the first two phases are to prevent complications, 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 help 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 overall goal of reconstructive surgeries (e.g. muscle/tendon transpositions of the intact arm or hand muscles) is to substitute for lost motor function (van Tuyl et al., 2002). According to Moberg (1975), over 60% of individuals with tetraplegia could benefit from reconstructive surgery (improve overall functioning and independence) (Snoek et al., 2004) and as such, surgical reconstruction is often advocated. However, suitable candidates often do not accept the treatment that is offered. Curtin et al. (2005) reported that fewer than 10% of persons with tetraplegia undergo surgical reconstruction.

Despite publication of clinical practice guidelines (Consortium for Spinal Cord Medicine 2005; Consortium for Spinal Cord Medicine, 1999), there is little consensus regarding the management of the tetraplegic upper limb. However, this may be due to variations in muscle function after SCI (Thomas et al., 2014). Understanding the diversity of 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.

Rehabilitation and management of an individual with 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.

The main focus of SCI rehabilitation is to train individuals on how to use their remaining sensorimotor systems to compensate for functional loss (van Tuijl et al., 2002). Rehabilitation strategies that utilize this method often demonstrate significant improvements in function after incomplete and 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). Functional improvements are thought to arise from new motor control strategies that the central nervous system (CNS) uses to govern various movements. In able bodied individuals, motor control strategies are determined by the CNS, which activates predefined combinations of muscles (muscle synergies) to perform a task, rather than explicitly controlling individual muscles (Zariffa et al., 2012a). This body of research could have important implications in neurorehabilitation, whereby retraining of muscle synergies through task performance may train the CNS to activate new motor control strategies. This process of “retraining” is known as adaptive plasticity (Frullo et al., 2017). 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 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).

3.0 Therapy Based Interventions
3.1 Exercise & Strengthening

Exercise as a rehabilitative therapy in SCI involves the use of repetitive and effortful muscle contractions to increase motor unit activity (Sandrow-Feinberg et al., 2009; Ada et al., 2006). Exercise may be classified as strength training or functional strength training. Strength training
involves isolation and stabilization of muscles through training protocols involving free weights or machines (Tomlijenovic et al., 2011), while functional strength training utilizes training programs centred around activities of daily living (Tomlijenovic et al., 2011). These exercises often involve multiple muscle groups and require functional movements that are more applicable to daily life, thereby improving strength for performing everyday tasks (Tomlijenovic et al., 2011).

Engaging in repetitive physical therapy that is active or passive has many beneficial effects for individuals with SCI including: preserved muscle mass (Houle et al., 1999), restored motor and sensory function (Hutchinson et al., 2004. Sandrow-Feinberg et al., 2009), induced synaptic plasticity by way of neurotrophic factor production (Vaynman et al., 2003), increased concentration of neurotrophic factors in spinal and muscle tissue (Gomez-Pinilla et al., 2002; Ying et al., 2005; Cote et al., 2011) and reduced inflammation around the lesion site (Sandrow-Feinberg et al., 2009). However, SCI often limits an individual’s ability to partake in exercise (Crane et al., 2015). This is a contributing factor to the incidence of obesity, cardiovascular disease and diabetes is two to four times higher in individuals with SCI compared to the general population (Evans et al., 2015).

Few evidence based analyses on the efficacy of specific exercise therapies on upper extremity function exist (Ginis et al., 2008). The majority of research has focused on individual components of physical capacity (e.g. peak oxygen uptake, muscle strength, or respiratory function), rather than functional outcomes. Additional studies regarding cardiovascular and exercise interventions are discussed in the Cardiovascular chapter and Physical Activity chapter.

The methodological details and results from seven studies evaluating exercise and strengthening for upper extremity function are presented in Table 1.

**Table 1 Exercise and Strength Training**

<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>Trumbower et al., 2017</td>
<td>USA</td>
<td>RCT – Crossover</td>
<td>PEDro=9</td>
<td>N=6</td>
<td>Population: Mean age=43±5 yr; Gender: males=6; Time since injury: 19±1 yr; Level of injury: C5; Severity of injury: AISA C=3, D=3. Intervention: Participants were randomized to normal or hypoxic conditions. Participants received daily (five consecutive d) acute intermittent hypoxia (AIH), which consisted of 15 episodes per day: 1.5 min of fraction inspired oxygen [FIO2] = 0.09, 1-min normoxic intervals) followed by 20 repetitions of hand opening practice and normoxia (sham FIO2=0.21). Treatments were followed by a two wk minimum wash out period. Outcome measures were assessed at baseline and one wk for each treatment group. Outcome Measures: Hand dexterity and function – Box and Block hand function test; Jebsen-Taylor hand function test (JTHF); Maximum hand opening.</td>
<td>1. Daily AIH and hand opening practice improved hand dexterity, function and maximum hand opening in all participants but was not statistically significant (p&gt;0.05). 2. AIH and hand opening practice significantly improved Box and Block Test scores versus controls in all 6 participants (p=0.016). 3. No statistically significant difference was observed in JTHF between groups (p&gt;0.05), however, all participants reduced their JTHF score after daily AIH and hand opening practice versus controls.</td>
</tr>
<tr>
<td>Study</td>
<td>Population</td>
<td>Intervention</td>
<td>Outcome Measures</td>
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<td>Nightingale et al., 2018</td>
<td>Mean age=47±8 yr; Gender: males=15, females=6; Time since injury: 16±11 yr; Level of injury: T4 and below; Severity of injury: not reported.</td>
<td>Participants were randomly assigned to a home-based moderate-intensity upper-body exercise intervention (n=13) or a lifestyle maintenance control group (n=8) for 6 weeks. Outcome measures were assessed at baseline and follow-up.</td>
<td>Physical and mental component scores (PCS and MCS); Health related quality of life (HRQOL); Fatigue; Global fatigue (FSS); WUPSI.</td>
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<td>Hicks et al., 2003</td>
<td>Age: 19-65 yr; Level of injury: C4-L1; Severity of injury: AIS A-D; Time since injury: 1-24 yr.</td>
<td>Experimental group (EX) participated in progressive exercise training twice weekly for nine mo-each session offered on alternative days lasting 90-120 min.</td>
<td>Perceived stress scale, Muscle strength, Depression, Physical self-concept pain, Perceived health, Quality of Life (QoL).</td>
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<td>Haisma et al., 2006</td>
<td>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.</td>
<td>Assessments were taken at four time points: start of inpatient rehabilitation; three months later; discharge and at one year after discharge.</td>
<td>Power output (PO) peak, VO2 peak, strength of upper extremity, respiratory function.</td>
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### Gant et al., 2018
**USA**  
**Pre-Post**  
**N=8**

**Population:** Mean age=31.4 yr; Gender: males=6, females=2; Time since injury: 10.5 yr; Level of injury: T2 - T10; Severity of injury: AIS A=4, B=4.

**Intervention:** Participants underwent three, four wk long multi-modal exercise conditioning and rehabilitation interventions, each separated by a one wk period of multiple body systems assessments. Each participant was in the trial for 19 contiguous weeks. Outcome measurements were assessed after screening for two baseline assessments and at four, nine, 14 and 19 wk.

**Outcome Measures:** Neurological motor and sensory impairment; Upper extremity muscle strength and peak oxygen consumption; Blood pressure; Cholesterol, lipids and biomarkers or glycemic control and inflammation; Clinical and electrophysiological spasticity measures; Pain history and pain-related sensory function; Self-reported function; Patient global impression of change.

1. No significant differences in neurological motor and sensory impairment, blood pressure, cholesterol, lipids, biomarkers of glycemic control and inflammation, as well as chronic pain were observed (p>0.05).
2. Upper extremity muscle strength significantly improved from baseline (p=0.001); Peak oxygen consumption was not significantly different from baseline (p>0.05).
3. Participants with high soleus (SL) and tibialis anterior (TA) F/M spasticity ratios at baseline improved significantly (p=0.001); Participants with high SL F/M spasticity ratios at baseline had a significant decrease in the Spinal Cord Assessment Tool for Spastic reflexes (SCATS) extensor score (p=0.047); Other measures of spasticity were not significant (p>0.05).
4. Two participants experienced clinically significant improvements in self-reported function (p<0.05).
5. All participants reported a perceived improvement.

### Hoffman et al., 2017
**USA**  
**Pre-Post**  
**N=17**

**Population:** Mean age=31.3 yr; Gender: males=10, females=7; Time since injury: 7.6 yr; Level of injury: C1 – C7; Severity of injury: AIS A=12, B=1, C=2, D=2.

**Intervention:** Patients with SCI were enrolled in a weekly hand-focused therapy program that involved using a novel handgrip device on grip strength and hand function. Outcome measures were assessed at baseline and once a wk until the end of the trial at 20 wk.

**Outcome Measures:** Maximum voluntary contraction (MVC); Mean absolute accuracy (MAA); SCIM.

1. The average MVC increased from 4.1N to 21.2N over 20 wk, but did not reach statistical significance (p>0.05).
2. The average MAA significantly increased from 9 to 21% at the end of the study (p=0.02).
3. The average SCIM was unchanged from baseline to the end of the study (p>0.05).

### Drolet et al., 1999
**Canada**  
**Pre-post**  
**N_{Initial}=40; N_{Final}=31**

**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 (OT) and physical conditioning. There were four 1 hr sessions of each intervention.

1. 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<0.001 shoulder adductors).
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.

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

Discussion

All seven studies presented found that exercise and strengthening was effective in improving upper extremity function. To date, these are the only studies that have tested exercise and strengthening for upper extremity rehabilitation in SCI. Interestingly, across all studies a wide variety of different types of exercise were efficacious. Trumbower and colleagues (2017) found that acute intermittent hypoxia, when combined with hand opening exercise improved hand function in individuals with SCI. Nightingale et al., (2018) investigated the efficacy of a home-based exercise program and found it improved health related quality of life. Hicks et al. (2003), Haisma et al. (2006) and Drolet et al. (1999), studied traditional in-patient exercise rehabilitation programs and found significant improvements in upper extremity function. Study participants also reported decreases in stress, pain, depression, enhanced physical self-concept and overall quality of life. Similarly, Hoffman et al. (2017) demonstrated significant improvements in hand function with the completion of a more traditional activity-based rehabilitation therapy. Gant et al. (2018) found significant improvements in upper extremity muscle strength with a multi-modal exercise training program. In this training program, a combination of activities was performed including body-weight-treadmill training, circuit resistance training for upper body conditioning, functional electrical stimulation and wheelchair skills training.

In summary, regardless of the training modality used, individuals experienced increases in muscle strength, hand function and quality of life. However, further research is necessary to directly compare the efficacy of each exercise/strength training program to each other. In addition, Haisma et al. (2006) and Sipski and Richards (2006) recommended further research in a variety of areas including optimal methods for strengthening muscles, merits of endurance versus strength training, and ROM, ADL, and transfer training. the impact of body composition, age, concomitant medical problems on exercise efficacy should also be explored. Furthermore, longitudinal studies are needed to gain more insight into the changes that occur after inpatient rehabilitation and the factors which influence these changes.
Conclusions

There is level 1b evidence (from one randomized controlled trial; Trumbower et al. 2017) that acute intermittent hypoxia combined with daily hand opening practice significantly improves hand opening in some, but not all, aspects of hand function.

There is level 1b evidence (from one randomized controlled trial; Nightingale et al. 2018) that six weeks of home-based upper-body exercise improves aspects of health-related quality of life.

There is level 2 evidence (from one randomized controlled trial; Hicks et al., 2003) that physical capacity continues to improve 1-year post discharge and is correlated to a decrease in stress, pain, and depression.

There is level 2 evidence (from one prospective controlled trial; Haisma et al. 2006) that physical capacity (strength and respiratory function) improve during and after inpatient rehabilitation.

There is level 4 evidence (from one pre-post study; Gant et al. 2018) that multi-modal exercise improves muscle strength and function in individuals with SCI.

There is level 4 evidence (from one pre-post study; Hoffman et al. 2017) that weekly activity-based hand therapy is feasible and efficacious at increasing hand task performance in individuals with SCI.

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.

Physical rehabilitation increases muscle strength and function to improve hand task performance and quality of life in individuals with SCI.

3.2 Orthoses
Upper limb orthotic devices (e.g., splints or kinesthetic tape) are a well-accepted therapy for the management of SCI, particularly in the acute phase of injury (Curtin, 1994; Krajnik & Bridle, 1992). They are generally used to minimize or prevent contractures, spasticity and pain through immobilization and protection/support of the joints, as well as soft tissue (Curtin, 1994; Krajnik & Bridle, 1992; Paternostro-Sluga & Stieger, 2004). Joint and muscle contractures can severely impact independence for individuals experiencing SCI. For example, elbow flexion contractures greater than 25 degrees significantly effect an individual’s ability to transfer and complete depression lifts 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 include: the resting pan or paddle splints, wrist extension splints (Futuro-type splint, long opponens splint and dorsal cock-up splint and spiral splint) and 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).

Although orthoses are widely used, few studies have investigated the efficacy of splinting for the management of upper limb function following SCI. The methodological details and results from three studies are presented in Table 2.

**Table 2 Orthoses**

<table>
<thead>
<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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<tbody>
<tr>
<td>Harvey et al., 2006</td>
<td>Australia</td>
<td>RCT</td>
<td>PEDro=8</td>
<td>N&lt;sub&gt;Initial&lt;/sub&gt;=44; N&lt;sub&gt;Final&lt;/sub&gt;=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>
</tr>
</tbody>
</table>
**DiPasquale-Lehnerz, 1994**

USA

RCT

PEDro=4

*N*<sub>Initial</sub>=13; *N*<sub>Final</sub>=9

**Population**: Age: 18-42 yr; Gender: males=12, females=1; Time since injury: 6–8 wk.

**Intervention**: Experimental group was given long or short orthosis to be worn at night (eight hours) as soon as the subject could tolerate it.

**Outcome Measure**: Pinch strength, Functional activity use, Jebsen-Taylor Hand Function (JTHF).

1. No significant differences were noted between the two groups—all subjects demonstrated improvement in hand function and pinch strength.
2. At eight wks the 13 subjects showed improvement in their performance on the checkers subtest (p<0.01), simulated feeding subtest (p<0.01), and the large light object subtest (p<0.01).
3. At the 12-wk marker, improvement could be seen on the card subtest (p<0.05).
4. An increase in pinch strength was noted at eight wks for all subjects (p<0.05) and at 12 wk nine remaining subjects (p<0.05).

**Portnova et al., 2018**

USA

Pre-Post

*N*=3

**Population**: Mean age=53 yr; Gender: males=1, females=2; Time since injury: 20.8 yr; Level of injury: C4 – C6; Severity of injury: not reported.

**Intervention**: Participants completed hand function tests with and without the use of a cost effective, 3D printed, wrist-driven orthoses (WDO).

**Outcome Measures**: Jebsen Taylor Hand Function Test (JTHF); Box-and-Blocks Test; Grasp strength (pinch dynamometry).

1. Varying improvements in hand function were observed with JTHF/Box-and-Blocks functional testing. One participant demonstrated improvement on the small object task, while another took 25 seconds longer.
2. Two participants had a significant increase in grasp strength with the WDO (p<0.05), while the other was able to perform a pinching grasp for the first time.

**Discussion**

Although splinting and orthotic fabrication is an accepted practice, there is minimal research on the effectiveness of this intervention (DiPasquale-Lehnerz, 1994; Krajnik & Bridle, 1992). A variety of splints serve similar purposes and little is known about what splint is best for the level and severity of SCI (Krajnik & Bridle, 1992).
In one RCT, Harvey et al. (2006) noted that twelve weeks of nightly splinting does not reduce thumb web-space contractures in individuals with a neurological condition (stroke, acquired brain injury, SCI). Even with careful monitoring of the fit of the splint, it was unclear if it was able to produce enough torque to the thumb joint for a sufficient stretch. The study also raised questions about the proper length of time an individual should spend wearing a splint, if the time spent wearing the splint was accurately reported and if there is a difference in outcomes when considering the type of neurological condition being splinted. Most importantly, clients and therapists perceived the splint as a major inconvenience. As time went on in the trial, patients became less compliant and both therapists and patients agreed that the overall effect of the splint needed to be substantial in order to justify the inconvenience and discomfort.

In one RCT, DiPasquale-Lehnerz (1994) found significant improvements in hand function (as measured by the Jebsen-Taylor Hand Function test) in subjects with tetraplegia who wore a long or short thumb orthosis while sleeping. Unlike Harvey and colleagues, a significant improvement in pinch strength and functional use (e.g., turning cards, and picking up small objects) was observed.

In one pre-post test, Portnoca et al. (2018) demonstrated varying improvements in hand function while using a wrist driven orthoses. For example, one participant improved their time to pick up small objects by 29 seconds, while another took 25 seconds longer. Moreover, two users significantly increased their grasp strength with the wrist driven orthoses. However, the limited number of participants in this trial (n=3) prevents a more conclusive understanding about the use of a wrist driven orthoses as an assistive device.

In summary, the choice of splint depends on an individual’s therapeutic aims and functional problem(s) resulting from the impairment(s), however, there is insufficient evidence from clinical trials on splinting strategies in SCI patients. This is supported by Paternostro-Slua and Steiger’s review (2004). Future research should focus on determining the efficacy of orthoses as rehabilitative or assistive devices, as well as the type and duration of splint necessary for different levels/severities of SCI.

**Conclusions**

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

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

*There is level 4 evidence (from one pre-post test; Portnoca et al. 2018) that wearing a wrist driven orthoses as an assistive device may improve hand function and grasp strength.*

Minimal clinical research evidence exists on the use of orthoses in preventing joint problems or improving hand function.
3.3 Skills Training and Education

Over time, there has been increasing interest and recognition in SCI-related education during rehabilitation. Patient education aims to help patients reintegrate into the community and improve quality of life through instruction on a variety of topics (Bernet et al., 2018; van Wyk et al., 2015). Educational topics that are often addressed include: learning how to self advocate, how to prevent, recognize and respond to adverse health complications, as well as coping strategies (Bernet et al., 2018). As a result, patients learn how to manage their everyday life, take responsibility for their health and assume an active role in the treatment process (van Wyk et al., 2015). Consequently, patients may feel more motivated and confident in their abilities to deal with the physical and psychological consequences of a SCI (van Wyk et al., 2015).

The efficacy of patient education in other chronic diseases, such as diabetes or arthritis, has been well documented. Multiple systematic reviews reported that patient education improves disease specific knowledge (Barlow et al., 2002; Bennett et al., 2009; Shaw et al., 2009; Coster & Norman, 2009) and reduces symptoms (Deakin et al., 2005; Gibson et al., 2009; Riemsma et al., 2009; Warsi et al., 2004). However, a lack of research investigating the effects of patient education or educational strategies in individuals with SCI exists.

The majority of skills training and education literature found focused on upper limb function in wheelchair use. The methodological details and results from these studies are presented in Table 3.

Table 3 Education and Skills Training Interventions

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Country</th>
<th>Research Design</th>
<th>Score</th>
<th>Total Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yeo et al., 2018</td>
<td>Korea</td>
<td>RCT</td>
<td>PEDro=7</td>
<td>N=24</td>
<td></td>
</tr>
<tr>
<td>Rice et al., 2014</td>
<td>USA</td>
<td>RCT</td>
<td>PEDro=8</td>
<td>N=93</td>
<td></td>
</tr>
</tbody>
</table>

**Population:** Intervention (n=13): Mean age=35.3±4.7 yr; Gender: males=10, females=3; Time since injury: 2.9 yr; Level of injury: T1 – C7; Severity of injury: AISA A=0, B=8, C=5, D=0.

Control (n=11): Mean age=35.9±5.3 yr; Gender: males=9, females=2; Time since injury: 2.8 yr; Level of injury: T1 – C7; Severity of injury: AISA A=0, B=7, C=4, D=0.

**Intervention:** Participants were randomized to a training group (n=13) or a control group (n=11). The training group attended wheelchair skills training sessions, whereas the control group attended conventional exercise sessions (three d/wk for eight wk). Outcome measures were assessed at baseline, four and eight wk.

**Outcome Measures:** Wheelchair skills test (WST); Van Lieshout test (VLT).

1. WST significantly improved over time compared with controls (p<0.05); WST significantly improved from baseline within the training group.
2. No significant differences occurred in VLT between groups over time (p>0.05); VLT significantly improved from baseline in both groups (p<0.05).
**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.

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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 6 mon 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 scores between 6 mon and 1 yr (p=0.07).

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

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

**Intervention:** 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.

**Outcome Measures:** Wheelchair User’s Shoulder Pain Index (WUSPI), Visual Analog Scale (VAS).

1. There were no significant differences between control and experimental group in age, yr of wheelchair use or activity levels.

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).

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

The majority of studies evaluated the effects of wheelchair education on preventing shoulder pain or increasing wheelchair skills. Rice et al. (2014) tested the efficacy of providing educational training using the PVA Clinical Practice Guidelines for Preservation of Upper Limb Function among manual wheelchair users. As a result of educational training, individuals with new SCI were able to increase their wheelchair skills to improve push frequency and length. However, no significant differences were reported in Craig Handicap Assessment and Reporting Technique (CHART) scores. Similarly, Yeo and colleagues found a significant increase in wheelchair skills with educational training (2018). However, both of these studies did not utilize outcome measures reporting on quality of life via ADL task assessment or functional independence measures (FIM). One study found that shoulder exercise education improved shoulder pain, which may translate to improvements in QOL, however this was not objectively measured (Curtis et al., 1999). In summary, providing patient education may improve wheelchair skills and reduce shoulder pain, however, it is unclear whether this directly impacts patient quality of life.

Further research in this area should focus on: (1) practical components of the educational program, (2) determining if differences in propulsion skills result in improvements in pain and/or quality of life, and (3) determining if improvements are maintained over the long-term.

**Conclusions**

*There is level 1b evidence (from two randomized controlled trials; Yeo et al., 2018; Rice et al., 2014) that education improves wheelchair skills.*

*There is level 2 evidence (from one randomized controlled trial; Curtis et al., 1999) that education about shoulder exercises reduces the intensity and duration of shoulder pain post SCI.*

Providing education to manual wheelchair users may be effective in improving wheelchair skills and preventing shoulder pain.
3.4 Motor Imagery

Motor imagery is defined as a cognitive process, in which a person imagines rehearsing a task without performing the physical movement (Scandola et al., 2017). Neuroimaging studies have demonstrated that motor imagery produces similar patterns of neural activation to those of motor execution, particularly in pre-motor areas such as the left intraparietal sulcus, basal ganglia, and cerebellum (Scandola et al., 2017; Athanasiou et al., 2018). Neuroimaging aside, motor imagery has shown the potential to assist in motor skill learning and rehabilitation for upper limb paralysis. In particular, motor imagery stimulated cerebral reorganization and improved motor functioning in patients with stroke and Parkinson’s disease (Page et al., 2009; Sun et al., 2013). Despite increasing interest in motor imagery for rehabilitative therapy, very few studies have investigated motor imagery for SCI rehabilitation.

The methodological details and results of these studies are presented in Table 4.

**Table 4 Motor Imagery**

<table>
<thead>
<tr>
<th>Author Year</th>
<th>Country</th>
<th>Research Design Score Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Di Rienzo et al., 2015</td>
<td>France</td>
<td>Pre-Post N=8</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. Intervention: 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). 2. MT were greater in SCI participants during the first pretest compared to the third pretests of the design (p&lt;0.01) but not in HC (p&gt;0.05). 3. In SCI participants, post-test MV was superior to the median pretest value (p&lt;0.05), but not in HC (p&gt;0.05). 4. The total number of SAM sources elicited during MI was similar in HC and SCI groups across experimental sessions (p=0.89). 5. Post-test values showing cortical recruitment (SAM sources) were significantly higher than those recorded during the pretests in the SCI group (p&lt;0.01) but not in HC (p&gt;0.05).</td>
</tr>
</tbody>
</table>
Di Rienzo et al., 2014
France
Pre-Post
N=12

**Population:** SCI participants (n=6); Age: 18-55 yr; Level of injury: C6/C7=6.
**Intervention:** 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 (HC) performing physical practice (PP)-based training.
**Outcome Measures:** Magnetoencephalography (MEG) measurements, Kinesthetic and Visual Imagery Questionnaire (KVIQ), Movement Time (MT), Movement Variability (MV).

1. Mean KVIQ visual and kinesthetic subscores, as well as KVIQ total scores were comparable in both groups (p=0.52).
2. Data from the mental chronometry task showed significant correlation between MI and PP durations at the whole-group level (p<0.001).
3. No significant difference between MI and PP durations (p=0.66).
4. A higher MV during the pre-test 3 as compared to the pre-test 2 in HP (p<0.05); in the SCI group, MV during the post-test 1 was significantly lower than during each of the pre-tests (all p<0.01).
5. Lower MT and MV in HP compared to SCI subjects, for each experimental session (all p<0.01).
6. There was no MV difference between post-test 1 and 2 in SCI participants (p>0.05).

**Discussion**

Two studies authored by one group of researchers tested the use of MI in improving motor learning post SCI.

Di Rienzo et al. (2014, 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.

Future studies should investigate the effect of completeness of the lesion on different types of MI in SCI. In addition, the effect of duration of injury, degree of autonomy, and presence of pain should be examined in relation to MI outcomes.

**Conclusions**

*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 movement time and variability performance.*
Motor imagery may be an effective intervention for improving movement performance in persons with SCI.

3.5 Action Observation

Action observation therapy has been used in the treatment of patients with neurological disorders, such as stroke and SCI (Peng et al., 2019). In action observation therapy, patients are asked to observe motor actions carried out by another individual and then attempt to perform the same task themselves (Peng et al., 2019). As an example, patients may watch a video clip that shows an individual stretching out their hand to pick up a cup and then try to attempt the movement themselves (Borges et al., 2018). This process is thought to enhance rehabilitation through the mirror neuron system by activating central representations of actions to increase cortical excitability in the primary motor cortex (Peng et al., 2019; Kim & Kim 2015). A few studies have evaluated the efficacy of action observation therapy in motor relearning following stroke and found some benefits in upper limb function (Kuk et al., 2016; Zhu et al., 2015; Sale et al., 2014; Ertlet et al., 2007). However, few studies have investigated the efficacy of action observation therapy in SCI patients.

The methodological details and results from one post test are outlined in Table 5.

Table 5 Action Observation

<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>
</table>
| Scandola et al. 2014 | Italy | Post Test | N=48 | 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 Control | 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 the 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. |
Discussion

There is very limited evidence to support action observation as a rehabilitative therapy for individuals with SCI. The results from Scandola et al., demonstrate significant improvements in feelings of hand ownership, however, the functional relevance of this remains unclear. As such, further research is necessary to determine the efficacy of action observation therapy in SCI.

Conclusion

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 limited evidence to support the use of action-observation therapy in SCI rehabilitation.

4.0 Technology Based Interventions

4.1 Virtual Reality

Virtual reality interventions facilitate rehabilitation through computer based, interactive, and multisensory experiences that occur in real time. Users are able to engage with simulated objects or events in a motivating and fun environment to develop a range of skills, movements or task-based techniques. Most importantly, virtual reality interventions meet the four guiding principles of rehabilitation: intensity, task-specific training, biofeedback and motivation (Dias et al., 2019). In addition, virtual reality based neuro-rehabilitation has been shown to engage the mirror-neuron system including the frontal, parietal and temporal lobes to encourage cortical reorganization and functional recovery (Kirshblum et al., 2004). In light of this, a variety of virtual intervention systems have been designed specifically for therapeutic use (e.g. Cyber Touch glove or Toyra) or
developed using existing gaming consoles (e.g. Nintendo Wii). As technology becomes increasingly accessible and affordable, virtual reality interventions have the potential to improve upper extremity function and transfer therapy gains into activities of daily living for innumerable people. Despite this, few studies have investigated the use of virtual reality interventions for upper extremity rehabilitation following spinal cord injury.

The methodological details and results of these studies (n=6) are presented in Table 6.

### Table 6 Virtual Reality Interventions

<table>
<thead>
<tr>
<th>Author Year</th>
<th>Country</th>
<th>Research Design</th>
<th>PEDro Score</th>
<th>Sample Size</th>
<th>Methods</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prasad et al., 2018</td>
<td>India</td>
<td>RCT</td>
<td>PEDro=7</td>
<td>N=22</td>
<td>Population: <em>Virtual reality and occupational therapy</em>: Mean age=23.7±5.2 yr; Gender: males=11, females=1; Time since injury: 15.2 mo; Level of injury: C5=5, C6=6, C7=1; Severity of injury: AISA A=1, B=6, C=2, D=3. <em>Occupational therapy</em>: Mean age=33.9±7.1 yr; Gender: males=10, females=0; Time since injury: 10.2 mo; Level of injury: C5=6, C6=3, C7=1; Severity of injury: AISA A=4, B=3, C=2, D=1. <strong>Intervention</strong>: Participants were randomized to receive a virtual reality intervention (using Nintendo Wii) along with conventional occupational therapy (n=12), or conventional occupational therapy alone (n=10). Outcome measures were assessed at baseline, 2, 4, and 6 wk post-intervention. <strong>Outcome Measures</strong>: CUE; BBT; SCIM.</td>
<td>1. No significant difference in hand function were observed between the groups for all outcome measures (p&gt;0.05).</td>
</tr>
<tr>
<td>Dimbwadyo-Terrer et al., 2015</td>
<td>Spain</td>
<td>RCT</td>
<td>PEDro=6</td>
<td>N=31</td>
<td>Population: <em>Conventional therapy and a virtual reality program</em>: Mean age=34.5±13.7 yr; Gender: males=10, females=6; Time since injury: 4.3 mo; Level of injury: C5=7, C6=3, C7=5, C8=1; Severity of injury: AISA A=11, B=5. <em>Conventional therapy</em>: Mean age=40.3±13.6 yr; Gender: males=12, females=3; Time since injury: 5.6 mo; Level of injury: C5=9, C6=2, C7=2, C8=2; Severity of injury: AISA A=10, B=5. <strong>Intervention</strong>: Participants were randomized to receive a virtual reality program in combination with conventional therapy (n=16) or only conventional therapy (n=15). The intervention group received 15 sessions with Toyra virtual reality system for 5 wk, 30 min/d, 3d/wk in addition to conventional therapy. Outcome measures were assessed at baseline, after intervention, and at a 3 mo follow up. <strong>Outcome Measures</strong>: MMT; FIM; SCIM III; BI; MB; MI.</td>
<td>1. The control group showed significant improvements in the manual muscle test (p=0.043) in the follow-up evaluation. 2. Both groups demonstrated clinical, but non-significant changes to their arm function. 3. No significant differences were observed between groups for SCIM III, FIM, BI, MB, or MI. 4. All patients showed a high level of satisfaction with the virtual reality system.</td>
</tr>
</tbody>
</table>
| Dimbwaydo et al., 2013  | Spain   | RCT             | PEDro=3     | N=14        | Population: **Intervention**: Time since injury: <6 mo; Level of injury: C5–C8. **Control**: Time since injury: <6 mo; Level of injury: C5–C8. **Intervention**: Participants were randomized to receive conventional therapy in addition to a virtual reality system (n=) for evaluation of ADLs or no virtual reality system and conventional therapy (n=). Outcome measures were assessed | 1. Significant improvements were observed in parameters related to dexterity, coordination and grip functions (p<0.05) after treatment in the intervention group. 2. No significant differences in kinematic variables and...
<table>
<thead>
<tr>
<th>Study</th>
<th>Country</th>
<th>Study Design</th>
<th>N</th>
<th>Population Details</th>
<th>Intervention Details</th>
<th>Outcome Measures</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimbwadyo et al., 2015</td>
<td>Spain</td>
<td>Pre-Post</td>
<td>9</td>
<td>Mean age = 54.3±9.9 yr; Gender: males = 5, females = 1; Time since injury: 5.8 mo; Level of injury: C4=1, T4=4; Severity of injury: AISA A=5, D=1.</td>
<td>Participants in the intervention group (n=6) underwent a virtual reality training program with the use of a data glove for two weeks, while participants in the control group (n=3) only underwent traditional rehabilitation. Outcome measures were assessed at baseline and at 2wk.</td>
<td>Outcome Measures: Dexterity; Coordination and grip functions; Kinematic and functional parameters.</td>
<td>1. No statistical significance was found in any of the outcome measures. 2. The data glove group seemed to obtain clinical changes in MB, functional parameters, dexterity, coordination and fine grip tests.</td>
</tr>
<tr>
<td>Seanez-Gonzalez et al., 2016</td>
<td>USA</td>
<td>Pre-Post</td>
<td>5</td>
<td>Mean age = 44.6 yr; Gender: males = 5, females = 0; Time since injury: 11.6 yr; Level of injury: C5 – C6; Severity of injury: Not reported.</td>
<td>Participants performed five visuospatial motor training tasks over 12 sessions (two to three sessions per wk). Subjects controlled a cursor with movements of the shoulders using a body-machine interface. Outcome measures were assessed at baseline and within two days of training completion.</td>
<td>Outcome Measures: MB; BI; SCIM; NHPT; JHFT.</td>
<td>1. The total MMT score improved significantly for all subjects after training (p=0.037). 2. The total isometric force exerted by the subjects’ shoulders improved significantly after 12 training sessions (p=0.012). 3. No significant differences were observed over time for the BDI or FIM (p&gt;0.05). 4. Motor training significantly increased FA, indicating localized white matter microstructure changes (p=0.03).</td>
</tr>
<tr>
<td>Dimbwadyo et al., 2015</td>
<td>Spain</td>
<td>Pre-Post</td>
<td>15</td>
<td>Mean age = 34.5±13.7 yr; Gender: males = 9, females = 6; Time since injury: 4.3 mo; Level of injury: C5=7, C6=3, C7=4, C8=1; Severity of injury: AISA A=10, B=5.</td>
<td>Participants received daily conventional therapy complemented with virtual reality ADL training. Outcome measures were assessed at baseline and 4 wk.</td>
<td>Outcome Measures SCIM; ROM.</td>
<td>1. A statistically significant improvement was observed in the total score of SCIM III self-care category and 2 of the 6 self-care category variables (Bathing upper body and Grooming) (p&lt;0.05). 2. ROM improved significantly when comparing pre- and post-assessments for 4 out of 5 ADL tasks (eating, drinking, spoon and sponge exercises) (p&lt;0.05). 3. No significant difference was observed pre and post assessment for the comb exercise (p&gt;0.05).</td>
</tr>
<tr>
<td>Foldes et al., 2015</td>
<td>USA</td>
<td>Post Test</td>
<td>3</td>
<td>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.</td>
<td>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</td>
<td>Outcome Measures</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</td>
</tr>
</tbody>
</table>
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. **Outcome Measures:** Grasp success rate, SMR modulation, time to successful grasp.

1. The percentage of trials containing a sub-movement did not differ significantly between the tetraplegic and control groups (p>0.1).
2. For % of type 3 sub-movements, there was a significant for direction (p<0.05), indicating that both groups made more type 3 sub-movement corrections when aiming away than toward the body.
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).

<table>
<thead>
<tr>
<th>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. <strong>Intervention:</strong> 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. <strong>Outcome Measures:</strong> Kinematic variables, Frequency and distribution (velocity, acceleration or jerk discontinuity), Amplitude and duration of sub-movements.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The percentage of trials containing a sub-movement did not differ significantly between the tetraplegic and control groups (p&gt;0.1).</td>
</tr>
<tr>
<td>2. For % of type 3 sub-movements, there was a significant for direction (p&lt;0.05), indicating that both groups made more type 3 sub-movement corrections when aiming away than toward the body.</td>
</tr>
<tr>
<td>3. A significant effect was shown in direction for movement time (p&lt;0.05) and a condition × direction × group interaction for both movement time (p&lt;0.01) and peak velocity (p&lt;0.05).</td>
</tr>
<tr>
<td>4. Peak acceleration indicated significance for group and direction (p&lt;0.02).</td>
</tr>
<tr>
<td>5. Primary movement amplitude was greater when aiming away from than toward the body (p&lt;0.05); this difference was somewhat larger in the vision than no vision condition (p&lt;0.05).</td>
</tr>
<tr>
<td>6. Amplitude revealed significance of group, with tetraplegics making larger corrections than controls (p&lt;0.05).</td>
</tr>
</tbody>
</table>
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 x direction x 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>
<thead>
<tr>
<th>Population: SCI population ($n=11$): Mean age: 37.5 yr; Level of Injury: C1-C4=5, C5-C6=6; Severity of Injury: AIS A=11. Non-injured group ($n=5$): Mean age: 29.8 yr. <strong>Intervention:</strong> Both the SCI and non-injured groups completed target matching tasks using a user command controller triggered by head position to manipulate a virtual hand representation. Participants using head movements matched the virtual hand to different targets. There 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). <strong>Outcome Measures:</strong> 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)).</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The non-injured participants had significantly faster TTC scores than the SCI participants on completing Targets 3 and 4 ($p&gt;0.05$).</td>
</tr>
<tr>
<td>2. Additionally, high cervical participants were found to have significantly slower TTC scores than the mid cervical group ($p&lt;0.05$).</td>
</tr>
<tr>
<td>3. The high cervical group had significantly higher IOE than the middle cervical group and the non-injured participants for Targets 3 and 4 ($p&lt;0.05$).</td>
</tr>
<tr>
<td>4. Non-injured participants had a significantly lower POE than those with SCI in completing Targets 3 and 4 ($p&lt;0.05$).</td>
</tr>
<tr>
<td>5. On examination of TTC, IOE and POE for Targets 5 and 6, no significant differences were found between SCI and non-injured participants ($p&gt;0.05$).</td>
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<tr>
<td>6. There was a significant increase in the TTC for Target 8 for SCI participants over non-injured participants ($p&lt;0.05$).</td>
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<tr>
<td>7. There was a significant increase in IOE for Target 7 by SCI participants when compared to non-injured participants ($p&lt;0.05$).</td>
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<tr>
<td>8. There was a significant increase in the POE commands for Target 7 and Target 8 for SCI participants compared to controls ($p&lt;0.05$).</td>
</tr>
<tr>
<td>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 ($p&gt;0.05$).</td>
</tr>
<tr>
<td>10. For speeds 1, 2, and 3, TTC scores were significantly lower for SCI participants ($p&lt;0.05$).</td>
</tr>
</tbody>
</table>
11. For IOE scores, non-injured participants had higher scores at speeds 1 and 3 compared to SCI participants (p<0.05).
12. For POE scores, non-injured participants were scored significantly lower than the SCI participants at all four speeds (p<0.05).

Discussion

In subacute and chronic stroke patients, improvements in upper limb function with virtual reality have been demonstrated; however, the evidence of its application in spinal cord injury is still very limited. The small number of studies presented here demonstrate that virtual reality interventions produce similar results to conventional therapy for upper limb function. A minority of studies, demonstrated significant improvement in aspects of hand function such as dexterity, coordination, and grip, as well as, specific activities of daily living. While the results of these studies are promising, they are rather preliminary. In this sense, virtual reality should not replace conventional therapy, however, it may be well suited as a supplement. The incorporation of virtual reality as a rehabilitation supplement has been shown to improve several motivating and social factors including perceived control, curiosity, exploration, imagination, cooperation, competition and social interaction (Lohse et al., 2013). Moreover, virtual reality may provide a more engaging treatment by allowing patients to interact with virtual objects in a variable environment selected by themselves (e.g. games, characters or levels). In turn, this may increase motivation and subsequently increase the dose of therapy received. However, as outlined by Prasad and colleagues, future research should focus on: (1) comparing virtual reality systems to conventional therapy with randomized controlled trials in a larger population, (2) development of telerehabilitation programs to compliment virtual reality intervention, and (3) efficacy of virtual reality systems and types of exercises included.

Conclusions

There is level 1b evidence (from two randomized controlled trials: Prasad et al., 2018, Dimbwadyo-Terrer et al. 2015) that virtual reality interventions (Nintendo Wii & Toyra) produce similar results to conventional therapy in upper limb function.

There is level 2 evidence (from one randomized controlled trial; Dimbwadyo-Terrer et al. 2013) that a virtual reality intervention (Toyra) significantly improves dexterity, coordination and grip functions in comparison to conventional therapy.

There is level 2 evidence (from one prospective controlled trial; Dimbwadyo et al. 2015) that a virtual reality intervention (Cyber Touch) produces similar results to conventional therapy and clinically improves dexterity, coordination and grip, although, not significantly.

There is level 4 evidence (from one pre-post test; Seanez-Gonzalez et al. 2016) that use of an interactive body machine interface in patients with high level SCI improves upper-body movement ability and stimulates structural brain changes.
There is level 4 evidence (from one pre-post test; Dimbwadyo et al. 2015) that conventional therapy complimented with virtual reality training (Toyra) for activities of daily living significantly improves self-care scores and range of motion in tasks related to eating, upper body bathing and grooming.

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 sensorimotor rhythms using a virtual hand task over time.

Rehabilitation using virtual reality interventions produces similar results to conventional therapy and may help to improve hand function, as well as activities of daily living, through an engaging platform as a supplement to conventional therapy.

4.2 Robotics

Recently, robotic devices were developed as a non-invasive solution to enhance intact motor pathways or manipulate the upper limbs for functional improvement (Capello et al., 2018). A number of different robotics are currently used for rehabilitation and they can be classified based on the type of robot, actuation method (energy source, e.g. electric motor), form of transmission (transfer of motion, e.g. cables) and sensors used (Yue et al., 2017). The two most common types of robotic devices used include end-effectors and exoskeletons (Yue et al., 2017). End-effectors are attached to the end of a robotic arm (e.g. robotic hand) and are designed to interact with the environment, externally to the patient (Yue et al., 2017). In contrast, exoskeletons are worn by the patient and include mechanical joints that align to the subject’s own joints, which assist the impaired user to move their own upper limbs (Sicuri et al., 2014; Yue et al., 2017; Capello et al., 2018). Importantly, both types of robotic devices may be used to deliver high quality and high
volume repetitions. It was recently suggested that repetitive movement exercise may promote functional recovery through the enhancement of adaptive plasticity (Frullo et al., 2017; Capello et al., 2018). A large body of literature has described the efficacy of robot-assisted rehabilitation for recovery of upper extremity motor function in stroke patients (Lo et al., 2010; Klamroth-Marganska et al., 2014; Frullo et al., 2017). However, there is a paucity of data on the efficacy of robot-assisted rehabilitation for recovery of upper extremity motor function in SCI. The methodological details and results from nine studies are listed in Table 7.

Table 7 Upper Limb Robotic Interventions

<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>Frullo et al., 2017 USA</td>
<td>PCT</td>
<td>N=17</td>
<td></td>
<td><strong>Population</strong>: Assist-as-needed (AAN) robotic controller: Mean age=53.5 yr; Gender: not reported; Time since injury: 16 yr; Level of injury: C3 – C6. <strong>Subject-triggered (ST) robotic controller</strong>: Mean age=53.5 yr; Gender: not reported; Time since injury: 16 yr; Level of injury: C3 – C6. <strong>Intervention</strong>: Participants were assigned to AAN or ST robotic controller groups. One wk after the last baseline visit, subjects started a program of robotic training, in ten 90-min long sessions, spread over a period of three to four wk. Outcome measures were assessed at baseline, one wk, two wk, and two mo after treatment. <strong>Outcome Measures</strong>: Action Research Arm Test (ARAT); Modified Ashworth Scale (MAS); Grip Pinch Strength assessment (GPS); GRASSP.</td>
<td>1. No significant difference was observed in the ARAT, MAS, GPS, or GRASSP scores or between groups (p&gt;0.05). 2. The AAN robotic controller demonstrated gradual improvement in movement quality over the ST robotic controller.</td>
</tr>
<tr>
<td>Capello et al., 2018 USA</td>
<td>Pre-Post</td>
<td>N=9</td>
<td></td>
<td><strong>Population</strong>: Mean age=49.8 yr; Gender: males=8, females=1; Time since injury: 26.9 yr; Level of injury: C4-C7, tetraplegia=9; Severity of injury: not reported. <strong>Intervention</strong>: Tetraplegic patients were administered a hand function test to assess the functionality of a soft robotic glove. Outcome measures were assessed at baseline without the assistive glove and once while wearing the assistive glove. <strong>Outcome Measures</strong>: Hand function during ADL tasks (Toronto Rehabilitation Institute Hand Function Test (TRI-HFT)); Object manipulation; Lift force.</td>
<td>1. The soft robotic glove significantly improved key hand functions to manipulate ADL objects and the mean score between baseline and assisted condition across all TRI-HFT categories (p&lt;0.05). 2. Lift force increased significantly when using the assistive soft robotic glove (p&lt;0.05).</td>
</tr>
<tr>
<td>Kim et al., 2017 Korea</td>
<td>Pre-Post</td>
<td></td>
<td></td>
<td><strong>Population</strong>: Mean age=33 yr; Gender: males=4; Time since injury: 12 yr; Level 1. Quantitative results showed that GRIPT users perform significantly better on accuracy and solidity of</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>Backus et al., 2014 USA Pre-Post</td>
<td></td>
<td></td>
<td>N=4</td>
<td></td>
<td>of injury: C5 – C6; Severity of injury: AIS A=2, B=2. <strong>Intervention:</strong> Participants compared writing performance using a new hand assist device (GRIPiT) to writing performance with a conventional penholder and their own hand without any device. Outcome measures were assessed at baseline and while using each assistive device. <strong>Outcome Measures:</strong> Quantitative outcomes: Accuracy of writing; Solidity of writing; Qualitative outcomes: Appearance; Portability; Difficulty of wearing; Difficulty of grasping; Writing sensation; Fatigability; Legibility.</td>
</tr>
<tr>
<td>Cortes et al., 2013 USA Pre-Post</td>
<td></td>
<td></td>
<td>N=10</td>
<td></td>
<td><strong>Population:</strong> 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. <strong>Intervention:</strong> 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. <strong>Outcome Measures:</strong> Motor performance, Corticospinal excitability, Upper extremity Motor score (UEMS), Visual analogue</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>
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<tr>
<td>Popovic et al., 1999</td>
<td>Yugoslavia</td>
<td>Pre-Post</td>
<td>N=12</td>
<td></td>
<td>Population: Mean age: 26.5 yr; Level of injury: C5-C7; Severity of injury: complete=10, incomplete=12; Length of experience with device: ≥6 mo.</td>
</tr>
<tr>
<td>Tigra et al., 2018</td>
<td>France</td>
<td>Post-Test</td>
<td>N=5</td>
<td></td>
<td>Population: Mean age=36.4 yr; Gender: not reported; Time since injury: 10.7 yr; Level of injury: C5 – C7; Severity of injury: AISA A=4, B=0, C=1, D=0.</td>
</tr>
</tbody>
</table>

1. Although no statistics were reported, all subjects were able to individually contract the tested muscles on demand for at least 7 s (indicated by EMG), except for one participant with no voluntary contraction. EMG signals were turned into functional commands to pilot the hand.
2. The tasks (holding an object in the robot hand for 5 s, open hand, palmar pinch and key grip) were successfully achieved with each tested muscle, however, no statistics were reported.

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 44.4±13.5 and 64.8±16.6 after six mo (increase of 20.4 points/46%).
3. Functional task completion: six subjects continued to use the device. On average, 75% of the functions were performed better after six mo of use. 6/12 (50%) did not continue to use the device. C6-C7 individuals may find the device beneficial enough to use it as an assistive device.
4. Technical improvements, specifically cosmetics, positioning of the electrodes, donning/doffing, should increase the number of regular users.
5. Best candidates are individuals with complete C6-C7 tetraplegia.
6. FIM score between 25-50 (up to 75), QIF between 0-13 (up to 27), are motivated to use it, can demonstrate efficient grasp.

7. 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 ($R^2=0.123$)
8. Initial UEMS and MEP amplitude had no correlation with the change on smoothness and aim.
<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>
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</thead>
<tbody>
<tr>
<td>Prochazka et al., 1997 Canada</td>
<td>Pre-Post</td>
<td>Pre-Post</td>
<td>N=9</td>
<td>Population: Age: 22-42 yr; Gender: males=8, females=1; Level of injury: C6-C7; Time since injury: 16 mo–22 yr.</td>
<td>Intervention: Use of bionic glove.</td>
</tr>
<tr>
<td>Coignard et al., 2013 France</td>
<td>Observational</td>
<td>N=63</td>
<td>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.</td>
<td>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.</td>
<td>Outcome Measures: Selection time (time between task’s &quot;start&quot; command and room/object selection click), Number of failures, Qualitative questionnaire.</td>
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<td>1. Mean peak force of tenodesis grasp in the nine subjects increased from 2.6 N±3.8 N (passive) to 11.3 N±7.4 N (glove active), significant than peak passive force (p=0.0064, t-test), and significant at end of fifth grasp 6.8 N±4.2 N, p=0.0064, Mann-Whitney rank sum test.</td>
<td>2. Most manual tasks improved significantly with the use of the glove.</td>
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<td>3. No significant difference between scenarios 1 and 2 in room/object selection, validation times and number of failures for controls and patients (p&gt;0.05).</td>
<td>4. Statistically significant difference between scenario 2 and 3 in object selection time for controls and patients (p&lt;0.05) but not for number of object selection failures (p&gt;0.05).</td>
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<td>5. 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&lt;0.05).</td>
<td>6. No significant patient versus control differences in the number of failures (p&gt;0.05).</td>
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<td>7. Experience of computer use had significantly affected speed of task for patients in scenario 3 (p&lt;0.05) and controls in all scenarios (p&lt;0.05).</td>
<td>8. Overall, the robot was found to be acceptable by both patients and control participants.</td>
</tr>
</tbody>
</table>

**Discussion**

The field of robotic devices for SCI rehabilitation is constantly evolving as technology advances. As a result of this, the majority of articles published in this area focus on testing newly designed robotic devices via non-randomized pilot studies that contain small sample sizes. Accordingly, it is difficult to draw any definitive conclusions about the efficacy of robotic rehabilitation itself. It is more appropriate to discuss emerging trends with specific types of robotic devices for SCI rehabilitation.

Several studies examined the feasibility and efficacy of robotic exoskeletons. All of the studies found that use of a robotic exoskeleton is feasible, however, the real world functionality of it may be limited and hard to use based on individual functioning. For example, one study found that use of a bionic glove was only successful in patients that had voluntary control over their wrist, while another found that at home use of the device may be impractical. In contrast, other studies
conducted using different types of exoskeletons (e.g. GRIPIT and a soft robotic based glove) found significant improvements in writing and hand function while wearing the device. The efficacy of exoskeleton use is controversial and may vary depending on the type of exoskeleton used and the overall functioning of the patient.

Only a few studies examined the feasibility and efficacy of an end-effector robotic device. However, all of the studies demonstrated improvements in upper extremity function while using the device. It should be noted that end effectors are robotic devices aimed at replacing upper extremity function instead of rehabilitating the patient. With the current technology available, robotic end-effectors are often cumbersome and large with complex interfaces. As such, Coignard and colleagues (2013) found that use of one at home is much less feasible than in a clinical setting. At present, this makes the feasibility of robotic end-effector rehabilitation fairly low. As technology advances, robotic end-effectors may evolve to be more adaptable in an at-home setting. Future research should focus on the long-term efficacy, as well as determining usability through functional impact questionnaires (e.g. FIM and ADL).

Conclusions

There is level 2 evidence (from one prospective controlled study; Frullo et al. 2017) that subject-adaptive upper extremity robotic exoskeleton therapy is feasible, however, no gains in arm function were observed.

There is level 4 evidence (from one pre-post study; Capello et al. 2018) that use of a fabric-based soft robotic glove significantly improves hand function when completing activities of daily living in individuals with SCI.

There is level 4 evidence (from one pre-post study; Kim et al. 2017) that the GRIPIT exoskeleton quantitatively and qualitatively improves writing when compared to conventional pen holders, although it is more difficult to wear.

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

There is level 4 evidence (from one post-test study: Tigra et al., 2018) that an end effector robotic device may improve hand grasping function in individuals with SCI.

There is level 4 evidence (from two case series; Popovic et al., 1999; Prochazka et al., 1997) that the Bionic Glove increases motor and upper limb function in individuals with SCI.

There is level 5 evidence (from one observational study; Coignard et al., 2013) that in a home environment the functionality of an end effector may be limited.

Upper extremity robotics improve hand function in individuals who have suffered upper limb paralysis following a spinal cord injury. However, further research is necessary to determine the efficacy of upper extremity robotic exoskeletons as part of a robotic rehabilitation program.
4.3 Brain Computer Interfaces

Brain-computer interface (BCI) technology utilizes brain signals instead of spinal or peripheral motor systems to drive external devices (Birbaumer et al., 2006; Collinger et al., 2013). These devices act as assistive technology to help individuals with SCI complete activities of daily living, without requiring physical movement (Huggins et al., 2015). In order to control a BCI, the user’s brain activity is recorded (via a neural recording device, e.g. EEG) while performing or thinking of performing a motor movement (Collinger et al., 2013; Van Dokkum et al., 2015). After recording brain activity, the information is decoded and turned into visual, auditory or haptic feedback and even the control of external devices to help facilitate movement (Collinger et al., 2013; Van Dokkum et al., 2015). Besides helping to facilitate movement, BCI technology may promote neuroplasticity through the recruitment of brain areas involved in motor planning and execution to operate training devices (Van Dokkum et al., 2015). However, BCI technology has only recently emerged as a rehabilitative treatment following SCI, therefore, the evidence base for this intervention rather limited.

The methodological details and results of eight studies evaluating BCI for upper extremity rehabilitation in SCI patients are presented in Table 8.

### Table 8 Brain Computer Interface Interventions

<table>
<thead>
<tr>
<th>Author Year</th>
<th>Country</th>
<th>Research Design</th>
<th>PEDro Score</th>
<th>Sample Size</th>
<th>Methods</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Osuagwu et al., 2016</td>
<td>UK</td>
<td>RCT</td>
<td>PEDro=6</td>
<td>N=12</td>
<td><strong>Population:</strong> Mean age=51.7±18.4 yr; Gender: males=12; Time since injury: Not reported; Level of injury: C4 – C7; Severity of injury: AISA A=0, B=4, C=8, D=0. <strong>Intervention:</strong> Participants were randomized to receive 20 sessions of BCI controlled FES (n=7) or the same number of sessions of passive FES (n=5), on both hands. Outcome measures were assessed at baseline and following treatment.</td>
<td>1. Patients in both groups initially had intense ERD during movement that was not restricted to the sensory-motor cortex. 2. Following treatment, ERD cortical activity restored towards the activity in able bodied individuals in the BCI-FES group only.</td>
</tr>
<tr>
<td><strong>Outcome Measures</strong>: Event related desynchronization (ERD); Somatosensory evoked potential (SSEP); ROM; MMT.</td>
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<td><strong>3.</strong> SSEP returned in 3 patients in the BCI-FES group, while no significant changes were observed in the FES alone group (p&gt;0.05).</td>
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<td><strong>4.</strong> All patients demonstrated increased ROM (median ROM for flexion and extension = 9.9 to 25.2) in both wrists following therapy except for one participant.</td>
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<td><strong>5.</strong> MMT significantly improved in all muscles groups in the BCI-FES group (p&lt;0.05), while the FES group improved shoulder muscles or muscles involved in controlling flexion (p&lt;0.05).</td>
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**Athanasiou et al., 2017**  
Greece  
PCT  
N=20

**Population**: SCI; Mean age=46.0±17.6 yr; Gender: males=8, females=2; Level of injury: T4 – C8; Severity of injury: AISA A=1, B=2, C=1, D=6.  
**Control**: Mean age=46.2±18.2 yr; Gender: males=8, females=2.  
**Intervention**: Participants with (n=10) or without SCI (n=10) operated two robotic arms via wireless commercial BCI, using motor imagery to perform 32 different upper extremity movements. Outcome measures were assessed after five training sessions with the BMI.  
**Outcome Measures**: Training skill; BCI control performance.  

| **1.** No significant differences were observed between groups for training skill or BCI scores. |
| **2.** The ability of SCI subjects to control robotic arms was not statistically different depending on injury location. |

**Pfurtscheller et al., 2009**  
Austria  
PCT  
N=15

**Population**: Mean age=41.0±14.5 yr; Gender: males=11, females=4; Time since injury: 86.1 mo; Level of injury: C5 – C12, paraplegia=8, tetraplegia=7; Severity of injury: Not reported.  
**Intervention**: Three types of motor imagery tasks were examined via EEG-based discrimination. Tetraplegic (n=7) and paraplegic (n=8) participants were asked to imagine using their right or left hand. Outcome measures were assessed during and after the tasks.  
**Outcome Measures**: Accuracy (EEG activity).  

| **1.** The average classification accuracy for left versus right hand was 65%. |
| **2.** In five out of eight paraplegic participants, the discrimination accuracy was greater than 70%. |
| **3.** Only one out of seven tetraplegic patients had a discrimination accuracy greater than 70%. |

**Foldes et al., 2015**  
USA  
Pre-Post  
N=3

**Population**: Mean age=28 yr; Gender: males=3, females=0; Time since injury: 7 yr; Level of injury: C2=1, C5=2; Severity of injury: AISA A=2, B=1.  
**Intervention**: Patients utilized a BCI for closing and opening a virtual hand to promote hand rehabilitation via therapeutic neuroplasticity. Participants performed 200 trials of hand control movements for approximately 30 min. Outcome measures were assessed after trial completion.  
**Outcome Measures**: BCI performance; Grasp success rate; Grasp or rest sensorimotor rhythms (SMR).  

| **1.** Participants were able to maintain brain-control of closing and opening a virtual hand with a significantly increased success rate of 63% (p<0.001). |
| **2.** Grasp success rates significantly increased for each participant (p<0.001). |
| **3.** Two out of three participants showed significant improvement in SMR (p<0.001), indicating they had learned to change their brain activity with a single session of training. |

**Pedrocchi et al., 2013**  
Italy  
Post-Test  
N=3

**Population**: Mean age=52 yr; Gender: males=3, females=0; Time since injury: XX yr; Level of injury: C3 – C7; Severity of injury: AISA Not reported.  

| **1.** The functionality of all modules was successfully demonstrated. |

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33
**Intervention:** Participants utilized a Multimodal Neuroprosthesis for daily Upper limb Support (MUNDUS) to perform different tasks related to ADLs, such as reaching and drinking. Outcome measures were assessed by three experts during completion of the task.

**Outcome Measures:** User intention; Evaluation score (from zero, unsuccessful, to 2, completely functional); Donning time.

1. User intention was detected with 100% success.
2. Averaging all subjects and tasks, the mean evaluation score was 1.6, with a minimum of 1.13.
3. All users, but one, subjectively perceived the usefulness of the assistance and could easily control the system.
4. Donning time ranged from 6 to 65 minutes.

**Population:** Age range=15-81; Gender: not reported; Time since injury: <10 yr; Level of injury: C1-C7; Severity of injury: incomplete=90, complete=60.

**Intervention:** No intervention. A technology survey to determine the likelihood of spinal cord injury patients adopting different technologies, given the burdens currently associated with them.

**Outcome Measures:** User preference for 8 BMI technologies including EEG, ECoG, intracortical microelectrode arrays and a commercially available eye tracking system.

1. Ninety-one percent of respondents with an injury level C1-C4 and 78% of C5-C7 who were <10 yr post injury said they are “likely” to adopt a BMI technology if it could restore some grasp of their hand or restore natural arm movement without sensation.
2. Control of external devices such as prosthetic (robotic) arms, computer cursors and wheelchairs was of moderately high interest to participants (>60% of C1-C4 respondents).
3. Participants were less likely to adopt these control capabilities if they were not described as being fast, accurate or natural.
4. High speed typing and control of a fast prosthetic (robotic) arm were of more interest than restoring less-than-natural native arm movement, via FES.
5. Surgically implanted wireless technologies were twice as “likely” to be adopted as their wired equivalents.
6. Thirty-nine percent of patients with C1-4 injury for 10 year or more were likely to adopt wired EEG caps, while 52% of the same population were likely to adopt the wireless intracortical technology.
7. Forty-eight percent of C1-C4 respondents and 45% of C5-7 respondents with less than 10 yr post injury were likely to adopt the wireless ECoG technology to restore some grasp of the hand. 60% of C1-4 and 46% C5-7 of the same group were likely to adopt wireless intracortical technology if it could restore some grasp of their hand.
8. Fifty-six percent of C5-7 and 80% of C1-4 respondents were more likely to adopt a
technology if it could control a cursor on a computer screen in a completely natural way.

9. Sixty-four percent of C5-C7 and 72% of C1-4 respondents, would be likely to adopt a technology if it would allow them to type at 40 words per minute with some errors.

Collinger et al., 2013
USA
Observational
N=57

**Population:** Mean age=55.2; Gender: male=51, female=6; Time since injury: 10.9 yr; Level of injury: tetraplegia=21, paraplegia=36; Severity of injury: not reported.

**Intervention:** No intervention. A survey of 57 veterans with SCI to determine priorities in improving quality of life, knowledge of assistive technologies and interest in BCIs.

**Outcome Measures:** Experience with assistive devices; Functional priorities; BCI technology.

1. Restoration of bladder, bowel control, walking, and arm and hand function (tetraplegia only) were all high priorities for improving quality of life.
2. Many of the participants had not used or heard of some currently available technologies designed to improve function or the ability to interact with their environment.
3. The majority of participants in this study were interested in using a BCI, particularly for controlling functional electrical stimulation to restore lost function.
4. Independent operation was considered to be the most important design criteria.
5. Many participants reported that they would consider surgery to implant a BCI even though non-invasiveness was a high-priority design requirement.

Onose et al., 2012
Romania
Observational
N=9

**Population:** Age range=33.1; Gender: male=8, female=1; Time since injury range: 6-202 mo; Level of injury: C4-C7; Severity of injury: AIS Frankel score one=4, two=3, three=2.

**Intervention:** Tetraplegic patients assessed the feasibility of a EEG-BCI for reaching/grasping assistance, though a robotic arm and completed a survey.

**Outcome Measures:** Accuracy; Perception; Side effects.

1. EEG-BCI performance/calibration-phase classification accuracy averaged 81%; feedback training sessions averaged 70.5% accuracy.
2. Seven out of nine (77.7%) patients reported having felt control of the cursor and 3 (33.3%) subjects felt they were controlling the robot through their movement imagination.
3. No significant side effects occurred.
4. BCI performance was positively correlated with beta EEG spectral power density (p=0.025) and AIS score (p=0.089).

**Discussion**

There has been considerable progress in neuroscience and technology, allowing for the development of aids for mobility regeneration. The emergence of neural interface technologies has provided an innovative approach to aid patients with sensorimotor deficits. All of the studies presented in Table 8 demonstrated that the use of BCI technology, although diverse, was feasible.
However, the efficacy of BCI technology varied between studies. One randomized controlled trial found that BCI-FES technology not only provided benefit as an assistive device but also improved neurological recovery and muscle strength, possibly through neuroplasticity (Osuagwu et al., 2016). Similarly, Foldes et al. (2015) found that a MEG based BCI improved sensorimotor rhythms to promote neuroplasticity following SCI.

The remainder of articles focused on BCI technology to control external devices. In these studies, it was found that control of a robotic device using BCI technology is feasible and individuals with SCI are interested in using the technology. In a survey that was conducted, 80% of respondents would consider adopting a BCI technology, if it could restore some hand grasp (Blabe et al., 2015). However, it was less likely to be adopted if it was aesthetically unpleasing, unreliable, difficult or embarrassing to use. It should be noted that participant performance on functional tasks was relatively poor. This may be due to the fact that participants needed more time training with the device or that the technology needs to be developed further to provide real benefit for self-assistance. Nonetheless, BCI is a promising rehabilitative device for individuals with SCI.

The importance of BCI applications in the future will depend on their reliability, and technological and functional advantages over conventional technology/rehabilitation. BCI technology has the potential to improve autonomy and independence in basic activities of daily life. For example, simple tasks such as drinking, eating, or moving hair away from the eyes can fundamentally improve quality of life and were identified as the most relevant by a focus group (Collinger et al., 2013). Despite the advantages of this technology, there are some drawbacks including increased donning times, cost and prototype technology that often needs improvement. Future research should focus on determining the long-term effects of BCI use and examine whether this technology could be adapted as a functional rehabilitative device.

Conclusions

There is level 1b evidence (from one randomized controlled trial; Osuagwu et al. 2016) that BCI-FES should be considered as a therapeutic tool rather than solely an assistive device, as combined BCI-FES therapy results in better neurological recovery and muscle strength than FES alone.

There is level 2 evidence (from two prospective controlled trials; Athanasiou et al. 2017; Pfurtscheller et al. 2009) that robotic control of a wireless or EEG controlled BCI is possible in SCI patients, however, multiple training sessions and tailored BCI algorithms are needed to improve performance.

There is level 4 evidence (from one pre-post test; Foldes et al. 2015) that a MEG based BCI may provide realistic, efficient and focused neurofeedback in SCI patients to promote neuroplasticity.

There is level 4 evidence (from one pre-post test; Pedrocchi et al. 2013) that the MUNDUS platform may provide functional assistance in activities of daily living to patients with SCI.

There is level 5 evidence (from two observational studies; Collinger et al. 2013 and Blabe et al. 2015) that individuals with SCI are interested in contributing to the design of BCIs and would adopt autonomous BMI systems for control of external devices or the restoration of upper extremity function.
There is level 5 evidence (from one observational study; Onose et al. 2012) that EEG-BCI-mechatronic devices may contribute real but limited potential for self-assistance in individuals with SCI.

BCI technology as a rehabilitative therapy is feasible and may be efficacious in promoting neuroplasticity; however, further technological advancement is necessary to provide benefit as an assistive device in tasks related to daily living at home.

4.4 EMG Biofeedback

Biofeedback is a non-invasive rehabilitative therapy that measures biological information and provides feedback to the patient (or therapist) to increase awareness and control over biological processes (Sturma et al., 2018). EMG measures the myoelectric activity of muscles and converts this data into visual and or auditory information (Sturma et al., 2018). Several studies have addressed the use of augmented feedback, such as biofeedback, with spinal cord injured populations. Van Dijik et al. (2005) conducted a systematic review of RCTs analyzing the effect of augmented feedback on motor function of the upper extremity in SCI patients. Much of the information about augmented feedback comes from motor learning literature where it has been noted that feedback combined with task practice enhances motor skill learning (Newell 1991; Schmidt & Lee 1999). There are two types of performance-related information or feedback. The first type of feedback is task intrinsic (inherent feedback). It involves sensory-perceptual information and is a natural part of performing a skill. The second type of feedback is augmented feedback (information-based extrinsic or artificial feedback). Augmented feedback refers to enhancing task intrinsic feedback with an external source (Magill 2001; Schmidt & Lee 1999), such as a therapist or device (biofeedback or timer) (van Dijik et al., 2005). It has been suggested that augmented feedback may have practical implications for rehabilitation therapy since re-acquisition of motor skills is an important part of functional motor recovery (Jarus 1994; Jarus & Ratzon 2005; Kilduski & Rice 2003; Weinstei 1991).
The ability to use intrinsic feedback to guide performance is impaired in patients with cognitive and perceptual deficits (Won & Radomski 2002). In persons who are compromised by sensory impairments, augmented feedback is important (Sabari 2001).

The methodological details and results of three studies evaluating EMG biofeedback for upper extremity motor rehabilitation in SCI patients are presented in Table 9.

Table 9 Augmented Feedback on Motor Functions

<table>
<thead>
<tr>
<th>Author et al., Year</th>
<th>Country</th>
<th>Research Design</th>
<th>PEDro Score</th>
<th>Initial Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
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<tbody>
<tr>
<td>Kohlmeyer et al., 1996 USA</td>
<td>RCT</td>
<td>NInitial=60; NFinal=45</td>
<td>PEDro=10</td>
<td>Population: Mean age: 39 yr; Gender: males=40, females=5; Level of injury: C4-C6; Severity of injury: complete, incomplete. Intervention: 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. Outcome Measures: 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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<tr>
<td>Klose et al., 1993 USA</td>
<td>RCT</td>
<td>NInitial=31; NFinal=28</td>
<td>PEDro=5</td>
<td>Population: Age: 18-35 yr; Gender: males=24, females=4; Level of injury: C5-C7; Time since injury: ≥1 yr. Intervention: 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. Outcome Measures: 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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<td>Brucker &amp; Bulaeva 1996 USA</td>
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<td>PEDro=10</td>
<td>Population: Age: 17-63 yr; Gender: males=81, females=19; Level of injury: C2-C6; Time since injury: 1-29.7 yr.</td>
<td>1. T-test analysis of the differences before and after initial biofeedback treatment was done. An increase of 19.21% of normal EMG scores for right triceps and increase of 0.09 (0.05,0.13) for left triceps was seen.</td>
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</table>

Klose et al. 1993; Biofeedback Training

T-test analysis of the differences before and after initial biofeedback treatment was done. An increase of 19.21% of normal EMG scores for right triceps and increase of 0.09 (0.05,0.13) for left triceps was seen.
Discussion

Two of the three studies concluded that there was no evidence for the effectiveness of augmented feedback to improve arm function in rehabilitation. These three 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 study did not include a control group.

In a systematic review, van Dijk et al. (2005) recommended the following be considered in future research in this area: (1) content, form, and timing of augmented feedback to clarify its importance in rehabilitation, (2) difference between performance and learning effects concerning reacquisition of motor skills by re-examining the study population after a follow up period.

Conclusions

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

*There is level 2 evidence (from one randomized control trial; 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.*

| Pre-post N=100 | **Intervention:** Electromyography (EMG) biofeedback treatment sessions.  
**Outcome Measures:** EMG scores. | 19.59% of normal EMG scores from the left triceps from one biofeedback treatment session were found, significant (p<0.001).  
2. **T-test analysis** of the difference from before initial biofeedback treatments to after additional treatments, increase in percentage of normal EMG scores of 41.55% right triceps and 38.31% left triceps, significant (p<0.001). Increases in percentage of normal EMG scores after initial biofeedback treatment to after additional biofeedback treatment 22.3% right triceps and 18.72% for left triceps, significant (p<0.001).  
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<0.001).  
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. |

EMG biofeedback does not improve motor function of the upper extremity in SCI rehabilitation patients.
4.5 Neuroprostheses

Neuroprostheses may provide the most promising gains in arm and hand function to individuals with SCI (Kilgore et al., 2018). Neuroprostheses utilize functional electrical stimulation or myoelectrically controlled systems to move prostheses or robotic end effectors. This is achieved through stimulation of residual motor nerves via transcutaneous, percutaneous, or implanted electrodes (Krucoff et al., 2016). Transcutaneous stimulation utilizes electrodes placed on the surface of the skin to stimulate a motor point of the muscle of interest (Baker et al., 1993; Mortimer, 1981), while percutaneous and fully implanted electrodes are placed under the skin or in the muscle to stimulate the motor nerve of the muscle of interest (Cameron et al., 1997; Hoshimiya & Nanda, 1989).

A variety of neuroprosthetic systems exist including the Handmaster-NMS-1, BGS, and ETHZ-ParaCare systems. All have been applied successfully as rehabilitation tools to restore grasping function in individuals with SCI. However, the most widely used neuroprosthesis for grasping is the Freehand system. Generally, to control the neuroprosthesis, individuals use an on/off switch or apply analog sensors to generate a desired command. There is usually a time delay of one or two seconds from command issue to grasp execution. Therefore, the speed that an individual can grasp and release objects is somewhat limited. Besides the technological drawbacks of neuroprostheses, an important barrier contributing to the use of neuroprostheses (or lack thereof) is the commercial availability of the device. Despite demonstrated improvements in upper extremity function and QOL following stroke or SCI, only one device is commercially available (Venugopalan et al., 2015). For a full list of the benefits and drawbacks of neuroprostheses, please refer to Table 10.

Table 10 Benefits and Drawbacks of Neuroprostheses Systems

<table>
<thead>
<tr>
<th>Benefits of Neuroprostheses</th>
<th>Drawbacks of Neuroprostheses</th>
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<tr>
<td>- Induces long term changes within the CNS (Popovic et al., 2002)</td>
<td>- Technology still being developed</td>
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<td>- Used as a rehabilitation system to promote recovery and better hand function as a permanent device</td>
<td>- Application is labour intensive</td>
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<td>- Augment grasp and manipulation functions required for ADLs.</td>
<td>- Acceptance of device by patient</td>
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<td>- Implantation may not be successful</td>
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<td>- Surgery</td>
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<td>- Technical and maintenance difficulties</td>
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<td>- Extensive training</td>
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Neuroprostheses can increase independence, reduce the need for other assistive devices, and decrease the time it takes to carry out activities of daily living (Kilgore et al., 2018). As such, neuroprostheses are typically used to complete tasks such as eating, drinking and personal hygiene. It is important to note that neuroprostheses are distinct from brain computer interfaces. Neuroprostheses connect any part of the nervous system to a device, whereas BCIs connect the brain with a computer and/or robotic system (Krucoff et al., 2016).

With advances in the technological capacity of neuroprostheses, many studies have examined their use in individuals with SCI. As such, the methodological details and results from 18 studies are presented in Table 11.

Table 11 Neuroprotheses post-SCI

<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>Kilgore et al., 2018</td>
<td>USA</td>
<td>Pre-Post</td>
<td>N=13</td>
<td>Population: Mean age=37 yr; Gender: males=10, females=3; Time since injury: 5.5 yr; Level of injury: C5 – C6.</td>
<td>Stimulation produced active extension and flexion for all five digits in all 15 arms studied, however, no statistics were reported. No subject had any active movement in their fingers or thumbs when the stimulation was turned off.</td>
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<td>Intervention: A surgically implanted myoelectrically-controlled neuroprosthesis was evaluated in 15 arms in individuals with cervical-level spinal cord injury. Outcome measures were assessed at baseline, one and three mo following surgery.</td>
<td>There was a significant increase in grip strength when the neuroprosthesis was turned on for all individuals (p&lt;0.0001).</td>
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<td>Using the neuroprosthesis, all 15 arms could manipulate at least 5 out of 6 objects, whereas only one hand could manipulate 4 objects prior to implantation.</td>
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<td>Outcome Measures: Active range of motion; Grip strength; Ability to pick up and release objects.</td>
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<td>Kilgore et al., 2008</td>
<td>USA</td>
<td>Pre-post</td>
<td>N=3</td>
<td>Population: Mean age: 34.0±9.5 yr; Level of injury: C5=1, C6=2.</td>
<td>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>
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<td>Intervention: A second generation neuroprosthesis system was implanted into individuals and functional outcomes were evaluated.</td>
<td>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>
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<td>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>ADLAT all three subjects improved in least five activities with one subject in all nine.</td>
<td>4.</td>
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<tr>
<td>Study</td>
<td>Age/Gender</td>
<td>Level of Injury</td>
<td>Time since injury</td>
<td>Intervention</td>
<td>Outcome Measures</td>
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<td>Peckham et al., 2001 USA Pre-post</td>
<td>Age: 16-57 yr; Gender: males=42, females=9; Level of injury: C5-C6; Mean time since injury: 4.6 yr.</td>
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<td>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.</td>
<td>Pinch strength, active ROM, Grasp-Release Test, Activities of Daily Living (ADL) Abilities Test, ADL Assessment Test &amp; user satisfaction survey.</td>
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<tr>
<td>Taylor et al., 2001 UK Pre-Post</td>
<td>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.</td>
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<td>No statistical results reported. 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.</td>
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<td>Carroll et al., 2000 Australia</td>
<td>Mean age: 29.1 yr; Gender: males=4, females=2; Level of injury: tetraplegia; Time since injury: 1.2-11.3 yr.</td>
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<td>There was significant improvement in lateral pinch and palmar grasp force after rehabilitation with and without the neuroprosthesis.</td>
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<tr>
<td>Study</td>
<td>Population</td>
<td>Intervention</td>
<td>Outcome Measures</td>
<td>Results</td>
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<tr>
<td>Pre-post N=6</td>
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<tr>
<td><strong>Intervention:</strong> The Freehand System – an implanted multichannel neuroprosthesis. <strong>Outcome Measures:</strong> Pinch forces, Grasp and Release Test (GRT), Activities of Daily Living (ADL) Test.</td>
<td></td>
<td></td>
<td>2. Force differences were not found between presurgery and rehabilitation without neuroprosthesis. 3. With neuroprosthesis, subjects could grasp, move and release more items in the 30 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. 5. After study, 5/6 subjects still used neuroprosthesis daily.</td>
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<tr>
<td>Mulcahey et al., 1997</td>
<td><strong>Population:</strong> Age: 16-18 yr; Level of injury: C6=5, Time since injury: &gt;1yr. <strong>Intervention:</strong> Implanted Freehand System. <strong>Outcome Measures:</strong> Grasp Release Test, Activities of Daily Living (ADL).</td>
<td></td>
<td>1. 40 electrodes implanted, 37 continued to work, all implant stimulators have functioned without problems with follow up ranging between 16-25 mo. 2. Grasp Release Test-lateral pinch and palmar grasp forces - Wilcoxon test, FES forces were significantly greater than tenodesis forces for both grasps (p=0.043).</td>
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<tr>
<td>Mulcahey et al., 2004</td>
<td><strong>Population:</strong> Age: 13-16 yr; Level of injury: tetraplegia; Time since injury: 4-16 wk. <strong>Intervention:</strong> 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. <strong>Outcome Measures:</strong> Muscle Strength-Pinch Force &amp; Hand Function, Performance of Activities of Daily Living (ADL), Satisfation with + without the Freehand System (Canadian Occupational Performance Measure (COPM)), Upper Extremity Capacity, Quadriplegic Index of Function.</td>
<td></td>
<td>1. No statistical results 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. 8. Freehand System Open-ended Questions-all subjects would repeat implantation.</td>
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<tr>
<td>Alon &amp; McBride 2003</td>
<td><strong>Population:</strong> Gender: males=7, females=0; Level of injury: C5-C6; Mean time since injury: 6 mo. <strong>Intervention:</strong> Subjects practiced with the neuroprosthesis 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></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>
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<tr>
<td>Study</td>
<td>Country</td>
<td>Study Design</td>
<td>N</td>
<td>Population</td>
<td>Intervention</td>
<td>Outcome Measures</td>
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<tr>
<td>Hobby et al., 2001</td>
<td>UK</td>
<td>Pre-post</td>
<td>9</td>
<td>Age: 16-55 yr; Level of injury: tetraplegia.</td>
<td>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.</td>
<td>Activities of Daily Living (ADL) tasks, Hand impairment measures (two grasp and release tests).</td>
</tr>
<tr>
<td>Snoek et al., 2000</td>
<td>Netherlands</td>
<td>Pre-Post</td>
<td>10; 4</td>
<td>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.</td>
<td>Training for use of Handmaster.</td>
<td>Activities of Daily Living (ADL).</td>
</tr>
<tr>
<td>Mangold et al., 2005</td>
<td>Switzerland</td>
<td>Case Series</td>
<td>11</td>
<td>Age: 15-70 yr; Gender: males=9, females=2; Level of injury: C5-C7; Severity of injury: AIS A-D.</td>
<td>FES was carried out with a stationary stimulation system and two portable systems (ETHZ-Paracare FES system, and Complex Motion).</td>
<td>Videos of functional tasks: hand function tests, Self-designed functional tests, Follow-up query-assessment of muscle strength.</td>
</tr>
<tr>
<td>Memberg et al., 2003</td>
<td>USA</td>
<td>Case Series</td>
<td>22</td>
<td>Level of injury: C5-C6.</td>
<td>Epimysial or intramuscular electrodes were implanted on the triceps. Following surgery standard stimulation exercise regimens were followed.</td>
<td>Activities of Daily Living (ADL) tasks, Hand impairment measures (two grasp and release tests).</td>
</tr>
<tr>
<td>Study</td>
<td>Country</td>
<td>Case Series</td>
<td>Population</td>
<td>Intervention</td>
<td>Outcome Measures</td>
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<tr>
<td>Taylor et al., 2002</td>
<td>UK</td>
<td>Case Series</td>
<td>N=9</td>
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<td>Population: Mean age: 38.4 yr; Gender: males=7, females=1; Level of injury: C4-C6; Mean time since injury: 10.1 yr.</td>
<td>Intervention: Assessment of the Freehand System.</td>
<td>Outcome Measures: Grasp Release Test, Grip Strength, Activities of Daily Living (ADL), Sensory ability (static 2 pt discrimination).</td>
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<td>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).</td>
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<td>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).</td>
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<td>3. Number of repetitions increased post implantation from 12.7 to 37.4 (p=0.028) and without the implant post-implantation (20.2, p=0.046).</td>
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<td>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.</td>
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<tr>
<td>Bryden et al., 2000</td>
<td>USA</td>
<td>Case Series</td>
<td>N=4</td>
<td></td>
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<td></td>
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<td>Population: Age: 23-48 yr; Level of injury: C5-C6.</td>
<td>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.</td>
<td>Outcome Measures: Five overhead reaching tasks, Amount of assistance required to complete the task, Survey of home use.</td>
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<td>1. No statistical analysis was completed.</td>
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<td>2. Passive elbow extension was within normal limits.</td>
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<td>3. With stimulated triceps subjects attained full elbow extension; without it full range was not met.</td>
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<tr>
<td>Wuolle et al., 1999</td>
<td>USA</td>
<td>Case Series</td>
<td>N\text{Initial}=42; N\text{Final}=30</td>
<td></td>
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<td></td>
<td>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.</td>
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<td>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%</td>
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</table>
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 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.

Kilgore et al., 1997
USA
Case Series
N=5

Population: Age: 28-57 yr; Level of injury: C5-C6; Severity of injury: complete; Time since injury: 2-9 yr.

Intervention: Implanted neuroprosthesis.


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
**Discussion**

A multitude of studies have investigated the feasibility and efficacy of neuroprostheses for SCI rehabilitation. Based upon the literature, a variety of neuroprostheses exist including myoelectrically controlled neuroprostheses, the Freehand system, Ness H200, and the EHTZ Paracare system. Despite several differences between these systems, all studies demonstrated that use of the system was feasible and more importantly, efficacious. All of the neuroprostheses used resulted in significant positive functional outcomes for individuals with SCI. However, the commercial unavailability of these devices impacts clinical use greatly.

The Freehand System results in significant positive functional outcomes for individuals with tetraplegia, however, there is limited opportunity for standardized clinical use at this time as the device is not commercially available. In addition, 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 widespread application of the Freehand System.

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 the extensor digitorum communis muscle at the volar side of the forearm. The second channel stimulates the flexor digitorium superficialis and profundus muscles. The third stimulation channel generates thumb opposition. The system is controlled with a push button that triggers hand opening and closing functions. The system is

<table>
<thead>
<tr>
<th>Smith et al., 1994</th>
<th>USA</th>
<th>Case Series</th>
<th>N=5</th>
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<tbody>
<tr>
<td><strong>Population:</strong> Age: 13-19 yr; Gender: males=5; Level of injury: C5-C6; Time since injury: 3-72 mo.</td>
<td><strong>Intervention:</strong> Intramuscular electrodes were implanted in the upper extremity muscles (Freehand System).</td>
<td><strong>Outcome measures:</strong> Breslow test.</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. 4. At 90 days after implant survivals probabilities of the finger + thumb extensors + thumb abductors were no significant than that of thumb adductor + flexor muscle groups.</td>
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<tr>
<th>Smith et al., 1996</th>
<th>USA</th>
<th>Case Series</th>
<th>N=5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Population:</strong> Age: 13-19 yr; Gender: males=3, females=2; Level of injury: C5=5; Time since injury: 3-72 mo.</td>
<td><strong>Intervention:</strong> Implanted Freehand System and tenodesis.</td>
<td><strong>Outcome Measures:</strong> CWRU Hand System (Case Western Reserve University), Grasp and Release Test.</td>
<td>1. With the implanted system and tenodesis each case of improved performance in later sessions was significantly better as compared to the initial session. (p&lt;0.05). 2. The average grasp forces with FNS increased: the range was from 8.9N (SD+5.2) to 22.5N (SD+8.6) and the palmar grasp forces increases from 2.1N (SD+2.9) to 11.1N (SD+6.0).</td>
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</table>
easy to don and doff. However, there are some limitations in its design: the rigid arm splint does not provide enough flexibility of the electrodes for stimulation of the finger flexors for grasp, and it is a stiff orthosis that fixes the wrist joint angle and prevents full supination of the forearm (Popovic et al., 2002).

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 (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).

In summary, neuroprostheses are a promising rehabilitative therapy for SCI. Use of a variety of systems demonstrates significant improvements in hand function and quality of life. However, the lack of commercial availability and invasiveness of surgery are deterrents to its clinical use. Future research should focus on developing an affordable and easily accessible neuroprosthesis system.

Conclusions

There is level 4 evidence (from two pre-post tests; Kilgore et al., 2018 and Kilgore et al., 2008) that a surgically implanted neuroprosthesis significantly improves grip strength/pinch force to enhance hand function and ADLs in individuals with SCI.

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 neuroprosthesis, individuals with SCI may regain grasp, hold and release abilities.

There is level 4 evidence (from eight case series; Mulcahey 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 one case series; Mangold et al., 2005) that the ETHZ-ParaCare neuroprosthesis is flexible (non-surgical) and has significant positive outcomes in rehabilitation and the ability to perform daily living tasks.

A variety of neuroprostheses exist that have demonstrated significant improvements in upper extremity function. As technology and surgical procedures advance, these systems may become more affordable and accessible for individuals with SCI.
Neuromuscular electrical stimulation (NMES) is a technique that utilizes electrical current to produce muscle contractions for the purpose of restoring motor function in individuals that have muscle weakness or paralysis (Knutson et al., 2019). In stroke patients, NMES has been shown to improve motor function recovery, especially when delivered in a way that assists patients in performing a task (e.g. walking or completing ADLs) (Howlett et al., 2015; Knutson et al., 2019). When combined with functional task practice, NMES is thought to improve recovery by promoting adaptive neuroplasticity (Kimberly et al., 2004; Rushton, 2003; Shin et al., 2008; Knutson et al., 2019). NMES generates muscle contraction by creating an electrical field near motor axons of peripheral nerves, which depolarizes the axonal membranes, consequently stimulating action potentials leading to muscle contractions (Knutson et al., 2019). Importantly, the strength of the muscle contractions can be modulated by changing the frequency, amplitude and duration of the current pulses. NMES can be applied transcutaneously with surface electrodes positioned over the target muscle(s), percutaneously with intramuscular electrodes that are connected to an external simulator, or subcutaneously with an implanted simulator (Knutson et al., 2019). Although NMES can be applied subcutaneously, most therapeutic applications are intended to be temporary and therefore non-invasive.

Despite the efficacy of NMES in stroke rehabilitation and potential application to SCI very few studies have investigated the effects of NMES in SCI rehabilitation. The methodological details and results from three studies are presented in Table 12.

### Table 12 Neuromuscular Electrical Stimulation Interventions

<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>
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<tbody>
<tr>
<td>Needham-Shrophire et al., 1997</td>
<td>USA</td>
<td>RCT</td>
<td>PEDro=8</td>
<td>N_initial=43; N_final=32</td>
<td>Population: Age: 18-45 yr; Gender: males=31, females=3; Level of injury: tetraplegia; Mean time since injury: 3 yr. Intervention: Subjects randomly assigned to one of three groups: Group 1 – received 8 wk of neuromuscular</td>
<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). 2. Subjects in Group 1 had a higher proportion of muscles improving one</td>
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stimulation (NMS) assisted arm ergometry exercise; Group 2 – received 4 wk of NMS assisted exercise, then 4 wk of voluntary arm crank exercise; Group 3 (control group) – voluntary exercise for 8 wk without the application on NMS. 

**Outcome Measures:** Manual muscle test.

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<0.05).

<table>
<thead>
<tr>
<th><strong>Klose et al., 1993</strong></th>
<th><strong>USA</strong></th>
<th><strong>RCT</strong></th>
<th><strong>PEDro=5</strong></th>
<th><strong>N_{\text{Initial}}=31; N_{\text{Final}}=28</strong></th>
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<tr>
<td><strong>Population:</strong> Age: 18-35 yr; Gender: males=24, females=4; Level of injury: C5-C7; Time since injury: ≥1 yr.</td>
<td><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.</td>
<td><strong>Outcome Measures:</strong> Manual muscle test, Functional activities score.</td>
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**Effect Sizes:** Forest plot of standardized mean differences (SMD±95%C.I.) as calculated from pre- and post-intervention data.

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

<table>
<thead>
<tr>
<th><strong>Cameron et al., 1998</strong></th>
<th><strong>USA</strong></th>
<th><strong>Case Series</strong></th>
<th><strong>N=11</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Population:</strong> Age: 18-45 yr; Gender: males=10, females=1; Level of injury: C4-C7; Time since injury: &gt;1 yr.</td>
<td><strong>Intervention:</strong> Testing of hybrid device, eight weeks of Neuromuscular Stimulation (NMS) assisted exercise with training sessions three times per week.</td>
<td><strong>Outcome Measures:</strong> Manual muscle test.</td>
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</table>

**Discussion**

Two out of the three studies presented demonstrated significant improvements in upper limb strength following NEMS rehabilitation therapy. Needham-Shophire et al. (1997) and Cameron et al. (1998) found that NEMS alone or in combination with exercise was effective for strengthening the upper limb in subjects with chronic SCI. However, Klose et al. (1993) found that exercise therapy combined with NEMS was no more effective than exercise alone. Despite promising evidence that NEMS may be an effective therapy for SCI, further clinical trials are necessary to truly determine efficacy.

**Conclusions**
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 2 evidence (from one randomized control trials; Klose et al., 1993) that the addition of NEMS does not improve patient scores in rehabilitation more than physical exercise alone.

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 mixed evidence about the efficacy of NMES to improve muscle strength.

5.2 Transcutaneous Electrical Nerve Stimulation

Transcutaneous electrical nerve stimulation (TENS) is a non-invasive treatment, traditionally used for pain management (Teoli et al. 2019). Electrical current is applied through surface electrodes on the skin, which facilitates activation of nerves (Teoli et al. 2019). The electrical current administered is highly adjustable with low frequencies (<10Hz) applied to produce muscle contractions and high frequencies (>50Hz) applied to produce paresthesia without muscle contractions (Teoli et al. 2019). More recently, TENS was found to have a potential role in the rehabilitation of motor function as the application of electrical stimulation at the sensory level may enhance neuroplasticity of the motor cortex (Veldman et al., 2015). Given the affordability of the TENS unit, its compact design and ease of clinical use, it is a promising rehabilitative therapy for SCI. However, very little research to date has focused on investigating TENS as a rehabilitative
therapy for SCI. The methodological details and results of one crossover RCT is presented in Table 13.

**Table 13 Transcutaneous Electrical Nerve Stimulation Interventions**

<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>Gomes-Osman &amp; Field-Fote</td>
<td>2015</td>
<td>USA</td>
<td>Crossover RCT</td>
<td>N=24</td>
<td></td>
<td>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. Interventions: 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.</td>
<td>Outcome Measures: Nine-hole Peg Test (9HPT), pinch strength, Corticomotor excitability/motor-evoked potentials, Visuomotor tracking task.</td>
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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: 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), Corticocmotor activity, Chedoke Arm and Hand Activity Inventory (CAHAI).

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

Population: 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.

Intervention: 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).

Outcome Measures: Jebson-Taylor Hand Function Test, Wolf Motor Function Test, Key pinch force, Monofilament testing, Motor evoked potential thresholds.

1. Intervention groups differed significantly in hand function (p<0.001). All intervention groups had a significant improvement in their hand function (MP, p<0.01; SS, p<0.05; MP+SS, p<0.001), as compared to the control group. The MP+SS group improved more than the MP and SS group alone (p<0.01).

2. MP+SS and SS groups significantly improved motor function scores when compared to the control group (p<0.001, p<0.05, respectively). MP+SS improved more than MP and SS alone (p<0.01).

3. MP+SS and SS groups also significantly improved pinch grip forces (p<0.01).

4. MP+SS was the only group to have a significant sensory function improvement (p=0.01).
<table>
<thead>
<tr>
<th>Study</th>
<th>Population</th>
<th>Intervention</th>
<th>Outcome Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beekhuizen &amp; Field-Fote 2005 USA RCT</td>
<td>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.</td>
<td>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) training focused on continuous repetitions of the following: gross upper extremity movement, grip, and grip with rotation, pinch and pinch with rotation. Tasks in each block were performed for 25 min before moving to the next category.</td>
<td>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.</td>
</tr>
<tr>
<td>Gomes-Osman et al. 2017 USA RCT PEDro=6</td>
<td>FTP + PNSS (n=14): Mean age=42.4±13.5 yr; Gender: males=12, females=2; Time since injury: 13.7±12.9 yr; Level of injury: C4 – C8; Severity of injury: AIS A=0, B=3, C=11, D=0. PNSS (n=13): Mean age=34.2±16.4 yr; Gender: males=12, females=1; Time since injury: 6.5±9 yr; Level of injury: C4 – C8; Severity of injury: AIS A=1, B=2, C=9, D=1. CET (n=10): Mean age=36.6±13.2 yr; Gender: males=6, females=4; Time since injury: 4±3.8 yr; Level of injury: C4 – C8; Severity of injury: AIS A=0, B=0, C=9, D=1.</td>
<td>Participants were randomized to one of two corticomotor priming approaches: functional task practice (FTP) plus peripheral nerve somatosensory stimulation (PNSS) (n=14), or PNSS alone (n=13), or to conventional exercise training (CET) (n=10). Participants were training two h daily, five d/wk for four wk.</td>
<td>Grip force (precision and power); Tactile sensation.</td>
</tr>
<tr>
<td>Gad et al., 2018 USA Pre-Post</td>
<td>Mean age=40.2 yr; Gender: males=5, females=1; Time since injury: 10 yr; Level of injury: C4 - C8; Severity of injury: AIS A=0, B=2, C=4, D=0.</td>
<td>Participants completed eight, one – two hr sessions of non-invasive transcutaneous stimulation, combined with voluntary hand grip training tasks over four wk. Outcome measures were assessed at baseline and at the end of the four wk training program.</td>
<td>Voluntary hand function (handgrip force).</td>
</tr>
</tbody>
</table>

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, 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).  
6. Cortical Excitability: No significant differences were noted between the two groups.  

1. Following intervention, significant improvements in precision grip force were observed in the stronger and weaker hand in the FTP + PNSS group (p=0.04).  
2. Significant improvements were observed in weak hand precision grip force with both PNSS (p=0.03) and CET (p=0.02).  
3. No significant changes were observed in power grip force or somatosensory scores in any group (p>0.05).  

1. Maximum voluntary handgrip forces increased significantly by 325% in the presence of stimulation and 225% when grip strength was tested without simultaneous stimulation (p<0.05).
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=3, AIS D=7; Mean time since injury: 24.1±22.1 yr.

Group 3 (n=5): Mean Age: 33.4±7.1 yr; Gender: males=3, females=2; Handedness: Rt=4, Lt=1; Level of injury: C5=2, C6=2, C7=1; Severity of Injury: AIS C=2, AIS D=3; Mean time since injury: 18.0±12.2 yr.

Intervention: Group I: 10 patients received massed practice (MP) training. Group II: 10 patients received somatosensory (SS) with massed practice. Group III: 5 patients received traditional rehabilitation program.

Outcome Measures: Maximal grip force, Wolf Motor Function Test (WMFT) timed score, Jebsen–Taylor hand function test score (JTHFT).

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 group II (p<0.05); but not in group I and III (p>0.05).
4. Pinch grip force showed a significant increase after treatment in group II (p<0.001) and group I (p<0.05) but not in Group III (p>0.05).
5. Comparison between pre and post-treatment WMFT timed scores showed significant decrease in group I and group II (p<0.05) but not in group III (p>0.05).
6. There was no significant difference between groups on JTHFT timed scores (p>0.05).
7. There was a significant decrease in group I and group II in JTHFT score post-treatment compared to pre-treatment value (p<0.05).

Discussion

There is considerable evidence that adding TENS to functional task practice significantly improves hand motor function and performance. All of the studies reported improvements in functional measurements such as the nine-hole peg test and pinch grip. However, it is important to note that outcome measures related to quality of life or activities of daily living were not reported. When evaluating TENS as a therapy by itself, the evidence is much more conflicting, with the majority of studies suggesting that TENS is not effective alone. Given the availability and low cost of TENS therapy, it may be a good adjunct to functional task practice for the improvement of arm and hand function; however, more clinical research is necessary to determine the long-term rehabilitative effects and impact on quality of life. Future research is also necessary to determine the efficacy of TENS therapy alone.

Conclusions

There is level 1a evidence (from one crossover RCT; Gomes-Osman & Field-Fote 2015 that TENS and tDCS, when combined with functional task practice improves aspects of hand-related function.

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 controlled trial; Gomes-Osman et al., 2017) that peripheral sensory stimulation combined with functional task practice improves grip force in individuals with SCI.

There is level 4 evidence (from one pre-post test; Gad et al., 2018) that transcutaneous spinal cord stimulation combined with hand grip training significantly improves hand function.

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.

When combined with TENS, functional task practice may improve aspects of hand-related function, however, more clinical trials to determine the long-term rehabilitative effects of TENS therapy are necessary.

5.3 Functional Electrical Stimulation

Functional electrical stimulation (FES) is a form of neuromuscular electrical stimulation (NMES) (see NMES section). Similar to NMES, FES involves the application of peripheral electrical stimulation to the nerves to activate muscles and induce movement of an impaired limb (Hodkin et al., 2018). However, FES simultaneously stimulates a number of muscle groups to coordinate movement of a functional activity such as cycling, standing or walking, unlike NMES (Bekhet et al., 2019). In a recent meta analysis, FES interventions improved activity in stroke patients when compared to no intervention and training alone (Howlett et al., 2015). The beneficial effects of FES are thought to arise from neuroplastic changes in motor circuits (Hodkin et al., 2018).
changes may be induced through the pairing of cortical and peripheral activity, whereby “cells that fire together, wire together” (Hebb’s principle) (Hodkin et al., 2018).

A total of seven studies investigating FES to enhance upper extremity rehabilitation were found. The methodological details and results of these studies are presented in Table 14.

**Table 14 Functional Electrical Stimulation Interventions**

<table>
<thead>
<tr>
<th>Author Year Country Research Design PEDro Score</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
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<tbody>
<tr>
<td><strong>Harvey et al., 2017 Australia RCT</strong></td>
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<td><strong>Population:</strong> Intervention (n=37): Mean age=29 yr; Gender: males=33, females=4; Time since injury: 81 d; Level of injury: Not reported; Severity of injury: AIS A=14, B=7, C=3, D=13. Control (n=33): Mean age=28 yr; Gender: males=28, females=5; Time since injury: 62 d; Severity of injury: AIS A=10, B=5, C=9, D=9. <strong>Intervention:</strong> Participants in the intervention group (n=37) received intensive training for one hand (training with an exercise workstation plus FES) for one h per d, five days per wk for eight wk. The control group (n=33) received conventional therapy and 15 min of one-to-one hand therapy three times per wk without FES. Outcome measures were assessed at 11 and 26 wk after randomization. <strong>Outcome Measures:</strong> Hand and arm function (Modified Action Research Arm Test).</td>
<td>1. No difference in hand and arm function was observed with intensive task-specific hand-training involving FES, standard care and three, 15 min sessions per wk of one-to-one hand therapy compared to controls (p&gt;0.05).</td>
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<td><strong>Popovic et al., 2006 Canada RCT</strong></td>
<td>N=21</td>
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<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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<tr>
<td><strong>Iwahashi et al., 2017 Japan RCT</strong></td>
<td>N=29</td>
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<td><strong>Population:</strong> Therapeutic electrical stimulation (n=15): Mean age=57.7±16.9 yr; Gender: males=15; Time since injury: 1 wk; Level of injury: Not reported; Severity of injury: Frankel grade B=6; Frankel grade C=9. Control (n=14): Mean age=59.4±18.5 yr; Gender: males=13, females=1 <strong>Intervention:</strong> Participants were randomized to either a therapeutic electrical stimulation (n=15) or control group (n=14). The therapeutic</td>
<td>1. There were no significant differences between any of the groups at three mo for all outcome measures (p&gt;0.05).</td>
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<tr>
<td>Author Year Country Research Design Score Total Sample Size</td>
<td>Methods</td>
<td>Outcome</td>
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<tr>
<td>Zoghi &amp; Galea 2017 Australia RCT PEDro=3 N=7</td>
<td>Electrical stimulation group received electrical stimulation through a neuroprosthesis for 5 to 20 min daily for four wk. Both groups received conventional therapy as well. Outcomes were assessed at baseline, one wk, one and three mo. <strong>Outcome Measures:</strong> Total passive motion of the fingers; Edema; Upper Extremity Motor Score of the International Standards for the Neurological Classification of Spinal Cord Injury (UEMS).</td>
<td></td>
<td>1. Some participants showed significant improvement after 8 wk of rehabilitation based on ARAT and GRASSP scores (p&lt;0.05). This improvement was not reflected in the pattern of muscle activation that was captured by BMCA.</td>
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</table>
| Hoffman & Field-Fote 2013 USA RCT PEDro=4 N=24 | Population: **Intervention (n=3):** Gender: males=3; Level of injury: C3 – C8; Severity of injury: AIS A=1, B=0, C=0, D=2. **Control (n=4):** Gender: males=3, females=1; Level of injury: C3 – C8; Severity of injury: AIS A=0, B=1, C=1, D=2. **Intervention:** Participants were randomized to a control group receiving the standard of care or an experimental group receiving the standard of care plus an intensive task-specific hand training program with FES for eight weeks. Outcome measures were assessed at baseline and every three mo for a yr. **Outcome Measures:** Upper limb brain motor control assessment (BMCA); Modified action research arm test (ARAT); GRASSP. | 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
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).

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).

**Effect Sizes**: Forest plot of standardized mean differences (SMD±95%C.I.) as calculated from pre- and post-intervention data.
<table>
<thead>
<tr>
<th>Author Year</th>
<th>Country</th>
<th>Research Design</th>
<th>Score Total</th>
<th>Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hodkin et al., 2018</td>
<td>U.K.</td>
<td>PCT</td>
<td>N=6</td>
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</table>

**Population:** Mean age=37±6 yr; Gender: males=6, Time since injury: 8±2 yr; Level of injury: C2 – C7; Severity of injury: AISA A=2, C=5

**Intervention:** Participants attended five FES sessions (one hour each, with a target of 200 repetitions per session) and aimed to complete blocks of 20 to 25 repetitions followed by one minute rests. Current values ranged from 20 to 35mA, stimulation pulse widths of 130 to 350µs, and stimulation frequency was fixed at 40Hz. The hand/side best suited to completing FES assistance, was trained during the intervention, while the untrained side acted as a control. Outcome measures were assessed before and after the intervention period.

**Outcome Measures:** Action Research Arm Test (ARAT); Qualitative feedback.

1. ARAT scores significantly increased on the trained side (3.4±1.1) when compared to the untrained side (0.1±0.8) (p=0.03).

2. Six out of seven SCI participants reported benefit from using the device, three out of seven reported improvements in ADL, cost and availability to devices was reported as a barrier to use.
Table 14.1 Functional Electrical Stimulation Systematic Reviews

<table>
<thead>
<tr>
<th>Author Year</th>
<th>Country</th>
<th>Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
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<tbody>
<tr>
<td>Patil et al., 2015</td>
<td>UK</td>
<td>Review of published articles between September 2009-September 2014 N= 5</td>
<td><strong>Method</strong>: Comprehensive literature search of full-length, peer reviewed studies of patients with complete or incomplete cervical SCI, investigating functional electrical stimulation (FES) (possibly comparing to other conventional therapies) in adult and human studies. <strong>Databases</strong>: EMBASE, PsycInfo, PubMed and Food, Science and Technology abstracts. <strong>Level of evidence</strong>: Jovell and Navarro-Rubio classification: <em>Good</em> (I-II): Meta-analysis of randomized controlled trials (RCTs); <em>Large-sample RCTs, non-randomized controlled prospective trials, non-randomized controlled retrospective trials; Good-to-fair</em> (III-V): Small-sample RCTS, non-randomized controlled prospective trials, cohort studies, case-control studies; <em>Poor</em> (VII-VIII): non-controlled clinical series; descriptive studies, anecdotes or case reports. <strong>Questions/measures/hypothesis</strong>: Examine the evidence for FES on motor control and functional ability of the upper limb in spinal cord injured people.</td>
<td>1. Two studies were scored a III, one study scored a VI, and two studies scored VIII. 2. In total, there were 10 different outcome measures between the five included studies assessing functional outcomes and motor control. 3. All 5 studies reported improvement, both immediate and follow-up, in motor control and functional ability of upper extremity as result of FES or FES with conventional therapy.</td>
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</table>

Discussion

Upon review of the literature, there is conflicting evidence on the efficacy of FES. Four randomized controlled trials found that FES has no added benefit over conventional therapy on upper extremity motor function. On the other hand, two randomized controlled trials, one prospective controlled trial and a systematic review found that FES improves motor control and function of the upper extremity. These discrepancies are likely due to differences in methodologies. An ongoing challenge in the FES field is determining what electrical stimulation patterns and duration of treatment are necessary. Future research should focus on determining effective electrical stimulation parameters. In addition, subject variability may also be a contributing factor to differences in outcomes and should be examined in further research. In summary, there is conflicting evidence to support the use of FES therapy.

Conclusions

*There is level 1b evidence (from two randomized controlled trials; Harvey et al., 2017; Popovic et al., 2006) that FES has no added benefit over conventional therapy.*

*There is level 2 evidence (from one randomized controlled trial; Iwahashi et al., 2017) that therapeutic electrical stimulation has no effect on upper extremity motor function.*
There is level 2 evidence (from two randomized controlled trials; Zoghi and Galea, 2017; Hoffman & Field-Fote 2013) that FES in combination with intensive hand task training improves upper extremity motor function.

There is level 2 evidence (from one prospective controlled trial; Hodkin et al., 2018) that multiple FES sessions improves upper extremity motor function.

The evidence is conflicting as to whether FES is effective alone or in combination with massed practice training.

5.4 Muscle Vibration

Adopted from: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0185936
To date, many rehabilitative therapies have been proposed to help with muscle function and spasticity, such as, passive standing, muscle strengthening and electrical stimulation (Ji et al., 2016). Recently, interest has focused on muscle vibration, which aims to prevent/treat muscle atrophy and spasticity through the application of mechanical oscillations to skeletal muscles (Ji et al., 2016). The application of vibration to muscle-tendon complexes results in a stretch-shortening action, in turn, activating muscle spindles to trigger a reflexive muscle contraction (Menendez et al., 2016). Vibratory stimulus may be applied in a variety of ways including focal muscle vibration and whole body vibration. Focal muscle vibration applies low-amplitude and high frequency vibration stimulation to a specific muscle through a small portable device (Celletti et al., 2017), while whole body vibration involves standing, sitting or performing various tasks on a vibration platform (Liao et al., 2015; Park et al., 2018). The effects of muscle vibration therapy have been well documented in stroke patients and demonstrate an improvement in motor function, as well as balance, gait and mobility. However, the effects of muscle vibration therapy on functional outcomes in individuals with SCI are not well known.

The methodological details and results from one randomized controlled trial are presented in Table 15.

Table 15 Muscle Vibration Interventions post-SCI

<table>
<thead>
<tr>
<th>Author</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>
| Gomes-Osman & Field-Fote | USA     | Crossover RCT   |       | N=24              | 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%CI) as calculated from pre- and post-intervention data.

<table>
<thead>
<tr>
<th>Gomes-Osman &amp; Field-Fote et al. 2015; TENS vs. VIB</th>
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<tbody>
<tr>
<td>Nine Hole Peg Test</td>
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<tr>
<td>Pinch Force</td>
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<tr>
<td>Visuomotor</td>
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<td>Motor Evoked Potential</td>
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<tr>
<th>Gomes-Osman &amp; Field-Fote et al. 2015; TENS vs. tDCS</th>
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<tr>
<td>Nine Hole Peg Test</td>
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<tr>
<td>Pinch Force</td>
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<td>Visuomotor</td>
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<td>Motor Evoked Potential</td>
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<tr>
<th>Gomes-Osman &amp; Field-Fote et al. 2015; VIB vs. tDCS</th>
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<tbody>
<tr>
<td>Nine Hole Peg Test</td>
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<td>Pinch Force</td>
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<tr>
<td>Visuomotor</td>
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<tr>
<td>Motor Evoked Potential</td>
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</table>

**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 (ISNCSI) 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 ISNCSI 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≤0.01) 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 post treatment and 3-mo post treatment (p=0.025).
Discussion

Currently, there is very little evidence to draw any conclusions about muscle vibration as a rehabilitative therapy in SCI. Given the evidence presented by Gomes-Osman & Field-Fote and Backus et al. (2014), vibration therapy is feasible in a SCI population. Pinch strength, muscle strength and grasp strength were temporarily improved with vibration therapy, however, no significant changes were observed with the nine-hole peg test or other measures of functional improvement. Based on the current evidence, muscle vibration therapy has little effect on functional outcomes in SCI patients. As such, future research is necessary in this area to determine the efficacy of muscle vibration therapy in SCI patients.

Conclusions

There is level 1a evidence (from one randomized controlled trial; Gomes-Osman & Field-Fote, 2015) that pinch strength significantly improves with vibration therapy but this does not translate to improvements in functional outcomes.

There is level 4 evidence (from one pre-post study; Backus et al., 2014) that an end effector utilizing muscle vibration can be safely used in patients with tetraplegia to significantly improve upper limb function.

More research is necessary to determine the efficacy of muscle vibration therapy in SCI rehabilitation.

6.0 Non-Invasive Brain Stimulation Interventions

6.1 Repetitive Transcranial Magnetic Stimulation

Transcranial magnetic stimulation (TMS) is a non-invasive and painless method of stimulating neural activity within the corticospinal system (Tazoe and Perez, 2015). A coil is placed on the scalp over an area of interest (e.g. motor cortex) to generate an electromagnetic field, which alters
electrical fields within the brain (Peterchev et al., 2012; Tazoe and Perez, 2015). Accordingly, this causes a change in neural membrane polarization, leading to an increase in neuron activity, transmission and activation of neural networks (Peterchev et al., 2012). This activity can be easily assessed using electromyographic recording electrodes to detect motor-evoked potentials (MEPs) – the output of the primary motor cortex (Tazoe and Perez, 2015). TMS may be applied as a single pulse or repetitively (rTMS) to elicit long-lasting significant improvements in aspects of sensory and motor function (Tazoe and Perez, 2015). The three main applications of rTMS in SCI are focused on improving sensory and motor function impairments, spasticity and neuropathic pain (Tazoe and Perez, 2015).

The methodological details and results from five TMS studies are listed in Table 16.

Table 16 Repetitive Transcranial Magnetic Stimulation Interventions

<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>
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<tbody>
<tr>
<td>Tolmachev a et al. 2017 Finland RCT PEDro=9 N=5</td>
<td></td>
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<td>Population: Mean age=48 yr; Gender: males=4, females=1; Time since injury: 3.8 yr; Level of injury: C3 – C7; Severity of injury: AIS A=0, B=1, C=3, D=1. Intervention: Participants were randomized to receive four wk (16 sessions) of transcranial magnetic stimulation (TMS) with peripheral nerve stimulation (PNS) to one hand and PNS combined with sham TMS to the other hand. Outcome measures were evaluated before the first stimulation, after the last stimulation, and one month after the last stimulation session. Outcome Measures: Daniels and Worthingham’s Muscle Testing scale.</td>
<td>1. One month after the last stimulation session, a significant improvement was observed in the TMS/PNS group (p&lt;0.0001). 2. The improvement was significantly higher in TMS/PNS than PNS treated hands (p=0.046).</td>
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</table>
| Gomes- Osman & Field-Fote 2014 USA RCT PEDro=6 N=21 | | | | 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. | 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
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).

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.

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

---

**Population**: Intervention (n=17): Mean age=47.5±12.3 yr; Gender: males=13, females=4; Time since injury: 6.8 yr; Level of injury: C3 – C8; Severity of injury: AIS A=2, B=0, C=11, D=4.

Control (n=14): Mean age=40.9±12.3 yr; Gender: males=8, females=6.

**Intervention**: Participants received paired corticospinal motor neural stimulation (PCMS) with transcranial magnetic stimulation (TMS) over the hand representation of the primary motor cortex, timed to arrive at corticospinal-motorneuronal synapses of the first dorsal interosseous (FDI) muscle 1-2 ms before antidromic potentials were elicited in motorneurons by electrical stimulation of the ulnar nerve (PCMS rest) or during small levels of isometric index finger abduction (PCMS active). Outcome measures elicited by TMS and electrical stimulation were measured in the FDI muscle before and after each protocol in participants with (n=17) and without (controls) (n=14) chronic cervical SCI.

**Outcome Measures**: Motor-evoked potentials (MEP).

---

**Population**: 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.

**Intervention**: Participants performed tasks requiring precision grip and index finger

1. In control participants, MEPs elicited by TMS and electrical stimulation increased to a similar extent after both PCMS protocols for 30 min.
2. In participants with SCI, MEPs elicited by TMS and electrical stimulation significantly increased after PCMS active versus PCMS rest (p=0.006).
3. SCI patients that did not respond to PCMS rest responded after PCMS active.
4. SCI patients that responded to both PCMS protocols, showed larger increments in corticospinal transmission after PCMS active.
abduction while noninvasive cortical and cervicomedullary stimulation allowed motor evoked potentials (MEPs). The activity in intracortical and subcortical pathways were examined.

**Outcome Measures:** EMG activity, F-wave amplitude and persistence, Suppression of voluntary EMG by subthreshold TMS (svEMG).

<table>
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<tr>
<th>Population: Intervention (n=5): Mean age=26.6 yr; Gender: males=5; Time since injury: 5.8 yr; Level of injury: C3 - C5. Control (n=12): Mean age=26.5±3.3 yr; Gender: males=9, females=3. Intervention: Tetraplegic patients who underwent biceps transfer (n=5) to enable elbow extension were compared to healthy controls (n=12) to determine whether multi-joint arm posture affects corticomotor excitability of surgically transferred biceps similarly to non impaired biceps. Single-pulse transcranial magnetic stimulation (TMS) was delivered to the motor cortex with the arm in functional postures at rest in intervention and control groups. <strong>Outcome Measures:</strong> Motor-evoked potential (MEP); Elbow extension.</th>
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<tr>
<td>1. MEP amplitude was significantly greater in the transferred biceps relative to non impaired biceps in overhead reach regardless of forearm orientation (p&lt;0.001).</td>
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<td>2. Arms with greater overall corticomotor excitability generated significantly greater maximum moments during elbow extension (p=0.029), which may be beneficial for elbow extension strength.</td>
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<tr>
<th>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). <strong>Outcome Measures:</strong> ASIA Impairment Scale (AIS), Nine Hole Peg Board.</th>
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<tr>
<td>1. No difference between patients when looking at the assessments done after baseline and after sham intervention.</td>
</tr>
<tr>
<td>2. The level of intracortical inhibition was reduced to 37.5±8.0% of pre-treatment levels during the week of therapeutic treatment (p&lt;0.05) and returned to 90.2±15% of pre-treatment levels during the follow-up period.</td>
</tr>
<tr>
<td>3. This was linked to improvements in clinical measures of both motor and pinprick of 4-10% during treatment week. (p&lt;0.05).</td>
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</table>
Subjects also improved perceptual threshold to electrical stimulation of the skin and peg board test scores (p<0.05).

Discussion

A limited number of studies have investigated the use of TMS in patients with SCI. The overall magnitude of improvements in functional outcomes was mixed. Significant improvements in muscle strength and functional task testing were observed in the majority of studies. Although, one study reported no significant change from baseline, while others reported mixed results based on the functional test used (e.g. pinch versus grasp). This might be related to the broad range of different methodologies used (e.g. stimulation parameters and types of patients). Regardless of these findings, TMS may be a promising approach to facilitate aspects of recovery after SCI. For example, Peterson and colleagues investigated the application of TMS after elbow extension reconstructive surgery and found enhanced motor recovery/plasticity. In conclusion, further research in this area is necessary to investigate potential applications of TMS and their functional contribution to SCI rehabilitation. Future research should focus on evaluating ADL and FIM outcomes, as well as rTMS in combination with other therapies.

Conclusions

There is level 1b evidence (from one randomized controlled trial; Tolmacheva et al., 2017) that TMS combined with PNS significantly improves muscle function of the hand.

There is level 1b evidence (from one randomized control trial; Gomes-Osman & Field-Fote, 2014) that rTMS may reduce corticospinal inhibition and enhance clinical/functional outcomes for several weeks after treatment.

There is level 2 evidence (from two prospective controlled trialz; Bunday et al., 2018; Bunday et al., 2014) that PCMS applied during voluntary activity may enhance spinal plasticity after SCI.

There is level 2 evidence (from one prospective controlled trial; Peterson et al., 2017) that TMS delivered to the motor cortex after elbow extension reconstructive surgery significantly improves elbow extension.

There is level 4 evidence (from one pre-post study; Belci et al., 2004) that TMS may lower intracortical inhibition and improve clinical motor scores.

rTMS has many applications and may improve functional outcomes alone or in combination with PNS and reconstructive surgery.

6.2 Transcranial Direct Current Stimulation
Transcranial direct current stimulation (tDCS) is a method of non-invasive brain stimulation that involves the application of low intensity electrical current (1-2 mA) to the head, via surface electrodes placed on the scalp in an area of cortical interest (James et al., 2018). In contrast to transcutaneous magnetic stimulation (TMS), tDCS modulates the resting membrane potentials of neurons rather than inducing action potentials to increase cortical excitability (James et al., 2018). To further enhance the electrical activity of neurons and promote activity-dependent neuroplasticity, tDCS may be paired with motor training (Siraman et al., 2014). In healthy individuals, tDCS is considered safe and efficacious as it is associated with bimanual coordination (Gomes-Osman et al., 2013). Moreover, its affordability and clinical accessibility make it an ideal treatment option for patients with SCI. Despite this, few studies have investigated the application of tDCS in SCI patients. The methodological details and results of these studies are presented in Table 17.

Table 17 Transcranial Direct Current Stimulation Interventions

<table>
<thead>
<tr>
<th>Author Year Country</th>
<th>Methods</th>
<th>Outcomes</th>
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<tbody>
<tr>
<td>Cortes et al., 2017 USA RCT – Crossover PEDro=7 N=11</td>
<td>Population: Mean age=44.9±12.9 yr; Gender: males=8, females=3; Time since injury: 8.2±5.7 yr; Level of injury: C5 – C7; Severity of injury: AIS A=0, B=5, C=5, D=1.</td>
<td>1. A significant improvement on grasp mean to peak speed ratio was observed in the 2mA group (p=0.031). 2. There was no statistically significant difference in BB test results (p&gt;0.05).</td>
</tr>
<tr>
<td>Potter-Baker et al., 2018 USA Cohort N=8</td>
<td>Population: Intervention: Mean age=52±1.6 yr; Gender: males=4; Time since injury: 4.5 yr; Level of injury: C2 – C6; Severity of injury: AIS A=0, B=1, C=0, D=3. Control: Mean age=55±2.4 yr; Gender: males=4; Time since injury: 13.6 yr; Level of injury: C3 – C5; Severity of injury: AIS A=0, B=1, C=0, D=3.</td>
<td>1. Participants receiving training paired with tDCS had increased strength of proximal (15% versus 10%), wrist (22% versus 10%) and hand (39% versus 16%) muscles immediately and</td>
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</table>
Intervention: Participants were randomized to receive massed practice training with or without transcranial direct current stimulation (tDCS). Outcome measures were assessed at baseline, after training and three mo following intervention.

Outcome Measures: Manual muscle test; Upper Extremity Motor Scores (UEMS); Action Research Arm Test (ARAT); Nine Hole Peg Test (NHPT).

Discussion

Numerous studies have investigated the effects of tDCS on cortical excitability in healthy subjects. However, the relationship of physiological changes due to tDCS stimulation in individuals with SCI remains unclear. As such, two studies recently investigated the effects of tDCS in chronic SCI patients for rehabilitation of upper extremity motor function.

In one RCT, Cortes and colleagues investigated the effects of one session of 1 mA, 2 mA and sham anodal tDCS on upper extremity motor performance (hand grasp and release) in patients with chronic cervical SCI. Although clinical assessment of hand function using the box and blocks test showed no difference between groups, a significant improvement in hand grasp was observed in the 2 mA group. This suggests that a single session of 2 mA tDCS may improve hand motor function, although future studies are necessary to determine whether tDCS may be an effective long-term rehabilitation strategy. Correspondingly, Potter-Baker et al. investigated the effects of pairing tDCS with massed practice rehabilitation training for several sessions over two weeks. Significant improvements in muscle strength were observed in weak proximal, wrist and hand muscles; however, no difference was observed between groups in clinical assessments. The lack of statistical significance may be due to the relatively small sample size. Despite this, the relative ease of integrating tDCS into routine clinical training for upper extremity rehabilitation in SCI patients, and the associated improvements in hand grasp/muscle strength, suggest further research is warranted. Future clinical trials should evaluate the efficacy of multiple tDCS sessions, as well as robotic-assisted training combined with tDCS.

Conclusions

There is level 1b evidence (from one RCT; Cortes et al., 2017) that a single session of tDCS significantly improves hand grasp in patients with chronic SCI, however, larger clinical trials are necessary to determine the effectiveness of tDCS as a long-term rehabilitation strategy.

There is level 2 evidence (from one cohort study; Potter-Baker et al., 2018) that tDCS paired with massed practice training may provide some advantage in improving the strength of proximal/hand muscles, however, larger clinical trials are necessary.
7.0 Pharmacological Interventions

7.1 Baclofen

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.” More recently, the EU-SPASM Thematic Network or Consortium (Support Network for the Assembly of Database for Spasticity Measurement) presented an updated definition of spasticity that reflects current research findings and clinical interpretations. Spasticity has been re-defined as “disordered sensorimotor 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 18 Pharmacological Intervention

<table>
<thead>
<tr>
<th>Author Year Country</th>
<th>Research Design</th>
<th>Score Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
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<tbody>
<tr>
<td>Burns &amp; Meythaler 2001 USA Case Series</td>
<td>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&lt;0.0001) and Ashworth scores (0.6 points, p&lt;0.0001) for the 1-yr follow-up period.</td>
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Discussion

Burns and Meythaler (2001) showed a statistically significant decrease in Ashworth and reflex scores in upper extremity hypertonia due to pathology at the level of the spinal cord. However, this is the only study published to date regarding intrathecal baclofen use in a SCI population.

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

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

8.0 Reconstructive Surgery and Tendon Transfers

One option when trying to improve hand and upper limb function in individuals with SCI is reconstructive surgery. Functionally, there are many benefits to reconstructive surgery including the improved ability to complete activities of daily living and improved quality of life for individuals that have minimal upper limb function (Freehafer et al., 1984; Kirshblum & Lin 2018). Despite the potential benefits, SCI patients often do not pursue reconstructive surgery. This decision has a myriad of sources, including being influenced by a temporal element and the hope for a cure or recovery from SCI (Sinnott et al., 2016). 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 (Sinnott et al., 2016).

8.1 Hand

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 results in many problems in daily living, particularly related to the preservation of independence (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 sexual function among persons with tetraplegia. In a survey of tetraplegia patients, 75% responded that hand function was very important for their independence in ADLs 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 wanted upper limb function restored first and 44% of the surveyed individuals reported an interest in receiving upper extremity reconstructive surgery (Wagner et al., 2007). More recently, Rivers and colleagues (2011) conducted a health-related quality of life survey and found that loss of upper extremity function significantly affects measures of functional independence negatively in subjects with SCI.

Although many studies have argued that up to 75% of persons with tetraplegia could benefit from hand surgery (Moberg et al., 1975; Wangdell et al., 2018; Anderson et al., 2009; Curtin et al., 2005; Rothwell et al., 2003), it is not common practice in many spinal centers. In the USA, it was found that only seven percent of appropriate surgical candidates actually received surgery (Curtin et al., 2005). Internationally, many barriers to reconstructive surgery exist resulting in an underutilization of surgery (Fox et al., 2015). Reasons for underutilization of reconstructive surgery have been identified including: lack of clarity in the literature about the value of reconstructive procedures, lack of access to centers that perform reconstructive surgeries, lack of qualified and experienced hand surgeons or physiatrists and negative physician bias toward reconstructive surgery (Curtin et al., 2005; Squitieri and Chung 2008). Several studies suggest only a small percentage of persons with tetraplegia benefit from hand surgery (Forner-Cordero et al., 2003; Guttman et al., 1976; McSweeney et al., 1969; Bedbrook et al., 1969). Many of these studies argue that with proper rehabilitation, individuals are able to re-adjust the function of their
arm and hands. Despite underutilization of surgery, 70% of individuals that do receive upper extremity surgery report satisfaction with their results and 68% report improvements in ADLs (Wuolle et al, 2003). These statistics are consistent with physician estimates of patient satisfaction, suggesting that both clients and medical professionals may view reconstructive surgery as beneficial and/or satisfying (Wagner et al., 2007).

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

In order to obtain functional pinch and grasp use, multiple, individualized procedures are often necessary. The type of reconstruction performed is also dependent on what muscles/tendons are present, if redundancy of function exists and if they are 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 was underpinned by 6 core influences: the overall outcome of surgery, current goals and priorities in life, potential for QOL improvement, a stable home environment, available social supports and assistance with 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.

Various types of reconstructive surgeries are performed to increase hand function in individuals with SCI. The type of reconstruction done and associated studies are presented below.

8.1.1 Pinch

Surgeries performed for reconstructive pinch include:
1. Key-Pinch Grip
2. Key-Pinch Grip with or without Hook Grip

Brachioradialis (BR) to flexor pollicis longus (FPL) Although none are very common, BR to FPL is typically performed with fusion of the thumb IP joint in combination with extensor carpi radialis longus (ECRL) to flexor digitorum profundus (FDP) for finger movement.

The methodological details and results from four pinch reconstructive studies are presented in Table 19.

Table 19 Pinch Interventions post-SCI

<table>
<thead>
<tr>
<th>Author Year Country Research Design Score Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
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<tr>
<td>Wangdell et al., 2018 Sweden Cohort N=37</td>
<td>Population: Experiencing pain (n=17): Mean age=43.6±13.4 yr; Gender: males=13, females=4; Time since injury: 6.1±9.5 yr; Level of injury: C5 – C7; Severity of injury: not reported. Not experiencing pain (n=20): Mean age=42.4±13.8 yr; Gender: males=11, females=9; Time since injury: 6.2±8.4 yr;</td>
<td>1. There were no significant differences between the pain and no pain groups regarding grip strength, grip ability or activity performance and satisfaction (p&gt;0.05). 2. Both groups experienced improvements in all aspects of the prioritized activity outcome and there</td>
</tr>
<tr>
<td>Author Year Country</td>
<td>Research Design</td>
<td>Score</td>
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<tr>
<td>House et al., 1992 USA</td>
<td>Case Series</td>
<td>N=18</td>
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<tr>
<td>McCarthy et al., 1997 USA</td>
<td>Pre-Post</td>
<td>N=135</td>
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<tr>
<td>Author Year</td>
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<tr>
<td>Waters et al., 1985</td>
<td>USA</td>
<td>Case Series</td>
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</table>
Discussion

All of the studies presented demonstrated significant improvements in upper limb function after pinch reconstruction surgery. Following the procedure, significant improvements in grip strength and finger flexion were demonstrated in multiple studies. Consequently, performance of ADL tasks improved, and individuals were able to gain more independence (McCarthy et al., 1997; House et al., 1992; Waters et al., 1985). As a result of this, the majority of subjects felt satisfied with the outcome of the procedure. Furthermore, Wangdell et al. (2018) found that even patients experiencing preoperative neuropathic pain benefited from pinch reconstruction surgery. Therefore, pinch reconstructive therapy is a viable option for patients who wish to receive surgery.

Conclusions

There is level 2 evidence (from one cohort study; Wangdell et al., 2018) that preoperative neuropathic pain has no effect on functional outcomes after surgical grip reconstruction.

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 overall 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.

Surgical intervention for recovery of upper limb function significantly improves motor outcomes and the ability to perform ADLs.

8.1.2 Pinch & Grasp

The most commonly performed surgeries to obtain key-pincher and hook grip are:

1. Wrist Extension
   - If the person does not have adequate wrist extension, BR to extensor carpi radialis brevis (ECRB) is performed prior to any surgery for pinch reconstruction.

2. Key-Pinch and Hook Grip
   - ECRL to 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. BR is also transferred to FPL.

The aim of these transfers is to provide mass finger flexion for grasp and independent thumb flexion for key-pincher against the side of the middle phalanx of the index finger. Adjustment of tension in these transfers is also completed (Lamb & Chan 1983).
The methodological details and results of 12 studies are presented in Table 20.

**Table 20 Reconstructive Surgery: Pinch & Grip**

<table>
<thead>
<tr>
<th>Author Year</th>
<th>Country</th>
<th>Research Design</th>
<th>Score</th>
<th>Methods</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coulet et al., 2018</td>
<td>France</td>
<td>PCT</td>
<td>N=31</td>
<td>Population: Mean age=34 yr; Gender: males=23, females=8; Time since injury: 7.3 yr; Level of injury: tetraplegia=31; Severity of injury: groups 1 to 5 of Giens international classification of tetraplegia levels.</td>
<td>1. Active key pinch strength was significantly higher than passive key pinch strength (p&lt;0.05) in patients who underwent CMC arthrodesis. 2. No significant differences in key pinch strength were observed in passive key pinch surgery patients with and without CMC (p&gt;0.05). 3. Active key pinch reconstruction with CMC arthrodesis hinders key pinch opening similarly to passive key pinch reconstruction. No significant difference was observed (p&gt;0.05). 4. No significant differences in key pinch stability were observed for either surgical technique (p&gt;0.05).</td>
</tr>
<tr>
<td>Mohindra et al., 2017</td>
<td>India</td>
<td>Pre-Post</td>
<td>N=12</td>
<td>Population: Mean age=42.2 yr; Gender: males=9, females=3; Time since injury: 6 mo; Level of injury: C6 – C8; Severity of injury: not reported.</td>
<td>1. Prior to surgery the average value for key pinch and hook grip was 0 kg; Following surgery, the average value was 1.67 kg for key pinch and 2.58 kg for hook grip at final follow up. 2. A significant increase in key pinch (p=0.0010) and hook grip (p=0.0015) was observed between 6 and 26 months demonstrating that gains achieved are maintained over time. 3. The Modified Lamb and Chan score revealed good to fair outcome in 75% of patients.</td>
</tr>
<tr>
<td>Forner-Cordero et al., 2003</td>
<td>Spain</td>
<td>Retrospective Follow-up</td>
<td>N&lt;sub&gt;initial&lt;/sub&gt;=15; N&lt;sub&gt;final&lt;/sub&gt;=14</td>
<td>Population: Age: 20-62 yr; Level of injury: C4-C7; Time since injury: 15-239 mo.</td>
<td>1. Strength: key-pinchen strength average of 17.2 kPa (5-50 kPa); grasp strength average 18.8 kPa (3-45 kPa). 2. No relation found between the ADL test and the key pinch strength (p=0.7976) or grasp strength (p=0.6948). 3. Modification of ADL questionnaire; excellent (3) 21.4%; good (7) 50.0%; fair (2) 14.3%; poor (2) 14.3%. Scores ranged from 54-122 points.</td>
</tr>
<tr>
<td>Meiners et al., 2002</td>
<td>Germany</td>
<td>Case Series</td>
<td>N&lt;sub&gt;initial&lt;/sub&gt;=24; N&lt;sub&gt;final&lt;/sub&gt;=22</td>
<td>Population: Age: 21-57 yr; Gender: males=21, females=3; Time since injury: 9-59 mo.</td>
<td>1. Operative interventions on the tetraplegic hand brings gains in cylindrical and lateral grip and improvement in ADL. 2. Subjective acceptance is high. 3. Complication rate is high. 4. Long duration of treatment.</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>
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| Lo et al., 1998 | Canada | Case Series | N=9 | | Population: Level of injury: C5-6; Time since injury: ≥1 yr. | 1. All reported they would have surgery again.  
2. Key pinch strength in non-op limbs was 1.0±1.3 kg, in surgically treated arms it was 1.2±1.1 kg.  
3. Minnesota rate of manipulation: non-operative limbs were 1.50±0.25 sec, post-operative limbs was 2 min 56 secs±1 min 56 sec. |
Intervention: Surgery.  
Outcome Measures: Key pinch, Grip strength, Activities of Daily Living (ADL). | 1. No statistical results reported-eight patients interviewed, five completed questionnaires.  
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. |
Intervention: Surgery.  
Outcome Measures: Range of motion (ROM); Finger flexion; ADL performance. | 1. No statistical analysis reported.  
2. Passive range of motion (ROM) of the elbow and wrist remained unchanged post-surgery. Functional active flexion of the fingers was gained in 10/11 subjects.  
3. Improved performance of Activities of Daily Living (ADL) was reported. |
| Rieser & Waters 1986 | USA | Case Series | N=23 | | Population: Mean age: 23.6 yr; Mean time since injury: 6.2 yr.  
Intervention: Surgery.  
Outcome Measures: Subjective rating of power. | 1. Self-assessment questionnaire results indicated: power decreased since surgery in all patients. |
| Kelly et al., 1985 | USA | Case Series | N=24 | | 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 & 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.  
Intervention: Surgery.  
Outcome Measures: Self reported surgery satisfaction and function; Key pinch; Grasp; Palmar pinch. | 1. Seven extremities had had post deltoid to triceps transfer before opponensplasty; 24 patients, 11 (46%) had bilateral opponensplasty.  
2. Thirty-five opponensplasties were done. 22 flexor tendon transfers were done for voluntary grasp and then opponensplasty.  
3. Fourteen patients (22 extremities) evaluated.  
4. Subjects reported that they would have the operation again (95% of the extremities) and had improved function (91%).  
5. One patient reported that function was unchanged; one was dissatisfied. Overall value of key pinch 35 extremities was 1.47±1.29 kg (mean± SD).  
6. Grasp measured in 20 extremities; 2.81±2.89 kg (mean±SD) (range trace to 10kg).  
7. Palmar pinch; 9 of 20 extremities (45%) achieved palmar pinch (1.04±1.02 kg; mean±SD) (range 0.20-3.0 kg). Palmar pinch achieved |
<table>
<thead>
<tr>
<th>Author Year</th>
<th>Country</th>
<th>Research Design</th>
<th>Score</th>
<th>Total Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colyer &amp; Kappelman</td>
<td>1981</td>
<td>USA</td>
<td>Case Series</td>
<td>N=8</td>
</tr>
<tr>
<td>Wangdell et al., 2014</td>
<td>Sweden</td>
<td>Observational</td>
<td>N=11</td>
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</table>

**Population:** Age: 16-36 yr; Time since injury: 4 mo-18 yr.

**Intervention:** Surgery.

**Outcome measures:** Self-reported satisfaction; Hand function; Key grip strength.

1. 6/8 subjects were evaluated. Subjects indicated they were pleased with the surgery.
2. Hand function tests indicated an improvement (16-49% improvement).
3. 5/6 subjects showed key grip strength remained constant.

**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 12 mo post-surgery at the patients’ home clinic. A grounded theory approach was adopted for analyzing the interviews.

**Outcome Measures:** Self-reported mood.

1. The patients’ responses revealed three phases of recovery; initiating activity training, establishing hand control in daily life, and challenging dependence.
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 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 also reported that home environments for practicing activities were more beneficial than clinics 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.
<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>Wangdell et al., 2013</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. 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: Self-reported physical ability and psychological mood.</td>
<td>6. After phase 3, a theme emerged of higher independence with patients stating several examples of autonomy.</td>
</tr>
</tbody>
</table>

1. The patients’ responses revealed three key areas that enhanced recovery; physical, psychological, and self-efficacy.
2. Self-efficacy was considered an important element in developing independence, especially when gripping and grasping objects. Self-efficacy was also revealed to be a motivator for further improvements and learning new skills.
3. Ability to perform more activities such as making food, picking up objects, opening/closing doors were among the practical aspects that enhanced independence. Participating in social activities (e.g. eating at a restaurant, sports/games, shopping), increasing levels of activity and decreasing dependence on assistance, and being less restricted by physical environments (i.e. improvising in environments not suited to their needs) were common themes for increasing independence.
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).

**Discussion**

A variety of key pinch and grasp procedures are presented in the literature. Importantly, 11 out of 12 studies outlined here demonstrate quantitative and qualitative improvement in hand function, as well as QOL. One study found that subjective ratings of power decreased after surgery, however, it is important to note that no objective measure of power was included in the study design. Regardless, key pinch and grasp function appears to be a successful rehabilitative therapy in SCI patients both psychologically and physically.
Conclusions

There is level 2 evidence (from one prospective controlled trial; Coulet et al., 2018) that active key pinch CMC reconstructive surgery increases key pinch strength when compared to passive key pinch reconstructive surgery.

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 and one pre-post test; Mohindra et al., 2017; 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 also report high satisfaction with their surgical results.

There is level 5 evidence (from two observational studies; Wangdell et al., 2013 and Wangdell et al., 2014) that patients report feelings of improvement, psychologically and functionally, after grip reconstructive surgery.

A variety of diverse pinch and grasp reconstructive procedures improve hand function and QOL.

8.2 Elbow Extension

Elbow extension is critical for many activities of daily living and individuals who lack elbow extension due to SCI are significantly functionally impaired (Medina et al., 2017). Everyday tasks such as getting dressed, propelling a wheelchair, transferring between a bed and a chair, and reaching for objects above shoulder level involve elbow extension (Medina et al., 2017). To restore elbow function, the two most common surgical techniques used are deltoid-to-triceps and biceps-to-triceps transfer (Kuz et al., 1999; Medina et al., 2017). A biceps to triceps transfer can be used to create elbow extension in patients who have active supinator and brachialis muscles (Kuz et al., 1999), both of which will replace the functions of the transferred biceps. The posterior third of the deltoid (PD) can be used to motor the triceps, converting the transferred portion of the deltoid into a two-joint muscle (Moberg, 1975). One additional option is to use the hamstring tendon to lengthen the connection between the deltoid and triceps.

8.2.1 Posterior Deltoid to Triceps

Posterior deltid-to-triceps transfer is the most commonly performed surgery for elbow extension. The methodological details and results of seven deltid-to-triceps transfer studies are outlined in Table 21.
Table 21 Reconstructive Surgery: Elbow Extension (Deltoid to Triceps)

<table>
<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>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. <strong>Intervention:</strong> 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°. <strong>Outcome Measures:</strong> 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°. 4. Length-tension relationship was fairly similar among control group, but great differences in experimental group.</td>
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<tr>
<td>Dunkerley et al., 2000 UK Case-Control N_initial=15; N_final=11</td>
<td>Population: Age: 23-38 yr; Time since injury: 5-16 yr. <strong>Intervention:</strong> Surgery. <strong>Outcome Measures:</strong> Questionnaire, Functional independence measure (FIM), 10m push, Figure of 8 push.</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). 3. Questionnaire was answered only by the treatment group; clients gave positive response to the questions.</td>
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<tr>
<td>Remy-Neris et al., 2003 France Pre-Post N=16</td>
<td>Population: Mean age: 27 yr; Gender: males=11, females=5. <strong>Intervention:</strong> 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. <strong>Outcome Measures:</strong> Straight Arm Raising, Hand-to-nape-of-neck movement.</td>
<td>1. Straight Arm Raising-statistically significant decrease in maximal shoulder abduction (mean 57 SEM 12 before, 14 SEM 6 after surgery). 2. Shoulder flexion increased after deltoid-to-triceps transfer by 42% (mean 113 SEM 11), remained significantly lower (121 SEM 12) than control group (p&lt;0.0001). 3. Hand-to-nape-of-neck-movement-no significant improvements were noted after surgery. 4. Peaks of shoulder and elbow flexion speed are almost normal, indicating the importance of restoring elbow extension torque for improving the whole kinematic picture of the upper limb.</td>
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<tr>
<td>Dunn et al., 2017 New Zealand Case Series N=75</td>
<td>Population: Mean age=31 yr; Gender: males=68, females=7; Time since injury: 23±9 yr; Level of injury: C4-C6; Severity of injury: AIS A/B=63, C/D=5, unknown=7. <strong>Intervention:</strong> No intervention. A retrospective chart review of deltoid-triceps transfers in patients with tetraplegia was performed between 1983</td>
<td>1. Following surgery, 70% of cases were able to extend their elbow against gravity (MRC grade 3 of 5 or greater); Hamstring grafts achieved grade 3 of 5 or more in 79% of cases compared with 77% tibialis anterior and 33% with synthetic grafts. 2. Post-surgery elbow extension increased significantly with</td>
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and 2014. Patients received tibialis anterior, synthetic or hamstring tendon grafts. Outcome measures were assessed prior to surgery and 12 to 24 months after surgery. **Outcome Measures**: Elbow extension strength (MRC); Complications.

3. Complications occurred in 14% of patients, the majority occurring immediately after surgery and associated with wounds, while the rest occurred due to dehiscence of synthetic grafts.

Lacey et al., 1986  
**Population**: Level of injury: C6-C7; Mean time since injury: 24 mo.  
**Intervention**: Surgery.  
**Outcome Measures**: ADL task performance.

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.

Raczka et al., 1984  
**Population**: Time since injury: 10-242 mo.  
**Intervention**: Surgery.  
**Outcome Measures**: Activities of Daily Living (ADL), use of wheelchair.

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.

**Discussion**

Upon review of the existing literature, the efficacy of deltoid-to-triceps transfer to restore elbow extension is seemingly controversial. On one hand, four out of the six studies reported functional improvement in activities of daily living, motor function, or self-reported satisfaction; conversely, two studies reported no significant differences in activities of daily living or functional independence measures pre- versus post-operatively. A possible explanation for these discrepancies is the relatively low sample size of the studies and the subjective nature of survey questionnaires completed in Dunkerley et al. (2000) study. Further research should investigate similar outcome measures with a larger population size, using objective outcome measures. Regardless, elbow extension surgery provided benefit to the majority of SCI patients that participated in these studies. Importantly, Rackza et al. (1984) noted functional improvements in many activities of daily living that lead to measurable improvements in independence. As surgical techniques advance, new and innovative approaches may improve the efficacy of elbow extension reconstructive surgery. As such, ongoing research must continually monitor functional outcomes related to elbow reconstructive surgery in SCI patients. Use of the hamstring tendon versus not has not been well studied and also needs to be accounted for with respect to outcomes.
One additional interpretation of the lack of efficacy may relate to not adequately capturing one important benefit from the surgery, reaching and increasing the client’s environmental access.

Conclusions

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 patient satisfaction with surgery.

There is level 4 evidence (from one case series; Dunn et al., 2017) that SCI patients receiving autologous tendon grafts experience increased elbow flexion and fewer complications than synthetic grafts for elbow extension reconstruction.

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

Deltoid-to-triceps surgery may improve motor function and the ability to perform daily living tasks, leading to satisfaction with the procedure.

8.2.2 Biceps to Triceps

Biceps-to-triceps transfer was first described in 1954 by Friedenberg and colleagues; however, its use was not popular in tetraplegic patients until 1975 by Zancolli. The technique does not require a stable shoulder and as a result, it can be applied in patients with high level cervical SCI (Medina et al., 2016). However, other muscles must be available to supply the biceps functions of flexion and supination of the elbow (Medina et al., 2016). In order to qualify for surgery, patients must have 5/5 elbow flexion of the MRC scale, active brachialis (ideally diagnosed with EMG or ultrasound), 3/5 supination with an active supinator and a supple elbow (Medina et al., 2016). If these requirements are not met, the patient will lose elbow flexion and forearm supination (Medina et al., 2016). In general, the surgery is safe, has a low rate of complications and post-operative follow-up is simple (Kozin et al., 2002; Medina et al., 2016). The procedure has some advantages over deltoid-to-biceps transfer in that it corrects flexion and supination deformities in one stage with one transfer, whereas deltoid-to-biceps may require two stages and two transfers. However, it is best considered for patients with supination and flexed elbow deformities. Upon review of the existing literature, four studies that investigated the use of biceps-to-triceps transfer for restoration
of elbow flexion in tetraplegic patients were identified. The methodological details and results of these studies are presented in Table 22.

Table 22 Reconstructive Surgery: Elbow Extension (Biceps to Triceps)

<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>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. <strong>Intervention</strong>: Surgery. <strong>Outcome Measures</strong>: Muscle strength, Flexion torque, Modified University of Minnesota Tendon Transfer Functional Improvement Questionnaire, Canadian Occupational Performance Measure (COPM), Activities of Daily Living (ADL).</td>
<td>1. After surgery, elbow extension muscle strength was improved in bicep and deltoïd groups (p&lt;0.001). 2. No significant increase in elbow extension muscle strength was found following surgery. 3. Seven of eight bicep-to-triceps procedures had clinical improvements in antigravity muscle strength, in comparison with one of eight deltoïd transfers completed. 4. No significant difference between the groups was found for elbow flexion torque (47% reduction in torque after two yr versus baseline). 5. Following surgery, 48/63 elbow extension ADL did not improve in subjects and there was no alteration in the remaining 15/63. 6. Performance and satisfaction with personal goals improved post-surgery as well.</td>
</tr>
<tr>
<td>Medina et al., 2017</td>
<td>Spain</td>
<td>Pre-Post</td>
<td>N=4</td>
<td></td>
<td>Population: Mean age=28.2 yr; Gender: males=4; Time since injury: 2.2 yr; Level of injury: C6, tetraplegia=4; Severity of injury: AISA A=2, B=2. <strong>Intervention</strong>: Tetraplegic patients underwent biceps-to-triceps transfer surgery according to Zancolli’s modified technique. Outcome measures were evaluated before surgery and 12 months after surgery, following standard rehabilitation. <strong>Outcome Measures</strong>: Elbow extension; Muscle strength assessment scale (MRC); Disabilities of the Arm, Shoulder, and Hand (DASH) questionnaire.</td>
<td>1. All patients that underwent the surgery achieved full and active elbow extension against gravity 12 months after surgery (M4 on MRC scale, substantial functional improvement of activities above their heads, and independence of transfers). 2. No significant difference in DASH score was observed pre (73.2±7.8) and postoperatively (30.8±13.4) (p&gt;0.05).</td>
</tr>
<tr>
<td>Kozin et al., 2010</td>
<td>USA</td>
<td>Case Series</td>
<td>N_{initial}=45; N_{final}=40</td>
<td></td>
<td>Population: Mean age: 17.3 yr; Level of injury: C5=10, C6=29, C7=1. <strong>Intervention</strong>: Surgery for a biceps to triceps tendon transfer (36 left, 32 right). <strong>Outcome Measures</strong>: Manual muscle testing, Canadian Occupational Performance Measure (COPM).</td>
<td>1. Manual muscle testing for elbow extension revealed a statistically significant increase in preoperative to postoperative muscle strength (p&lt;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.</td>
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</table>
Discussion

The main goal of elbow extension reconstructive surgery is to provide functional improvement of the upper extremities and independence. When individuals with SCI lack active elbow extension, simply raising their hands above shoulder level is not possible due to the difficulty of holding the elbow against gravity. This also makes positioning the hand in space and coordinated movement, such as writing or using a key, challenging. Therefore, in biceps-to-triceps transfers, strategic reanimation of the elbow is performed to enhance these functions once again.

Of the four studies that evaluated the efficacy of biceps-to-triceps transfers to surgically restore elbow function, the majority found the procedure to be effective. Mulchaey et al. (2003) found an improvement in bicep and deltoid muscle strength as well as performance and satisfaction. However, they did not report a significant improvement in active elbow flexion or performance of activities of daily living. The remaining studies all reported an increase in elbow function in areas such as elbow flexion, manual muscle test scores, COPM, self-reported surgery satisfaction and performance of activities of daily living post-surgical intervention. In one study, it was found that activities requiring precision hand placement had improved and the need for some adaptive aids was eliminated.

In summary, the biceps-to-triceps technique is a safe, simple and effective procedure that may be used to restore elbow flexion in tetraplegic patients. As surgical techniques advance, continuing research in this area is necessary.

Conclusions

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 test; Medina et al., 2017) that biceps-to-triceps transfer significantly improved upper extremity functional outcomes in individuals with SCI.

Biceps-to-triceps elbow extension is a viable surgical option for those with limited function, impacting activities of daily living.

8.3 Multiple Reconstructions

The methodological details and results from 13 studies that report results from multiple procedures to reconstruct the upper limb are listed in Table 23.

**Table 23 Multiple Reconstruction post-SCI**

<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>Dunn et al., 2014 New Zealand Cohort</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. Outcome Measures: Lamb &amp; Chan questionnaire (LCQ), Key pinch strength, Grip strength, Type of wheelchair used.</td>
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<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, three items were found to have worsened with 10 patients reporting a decline in their ability to propel their wheelchair up and down a slope, and the ability to propel their wheelchair on a level surface. 5. Further, 7 patients reported a decline in the ability to raise themselves from their seat on the LCQ.</td>
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<td>Friden et al., 2012b Sweden Case Control</td>
<td>Population: Treatment group (n=6): Mean age: 32.2±4.9 yr; Gender: males=4, females=2.</td>
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<td>1. Post-operative active pronation was significantly greater in the dorsal transfer group in comparison to the</td>
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<td>Author Year Country</td>
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<td>Friden et al., 2012a Sweden Pre-post N=15</td>
<td>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).</td>
<td>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>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. 4. 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.</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. Outcome Measures: Custom satisfaction survey.</td>
<td></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</td>
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91
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<tr>
<th>Author Year</th>
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<th>Total Sample Size</th>
<th>Methods</th>
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<tr>
<td>Friden et al., 2014 Sweden</td>
<td>Case Series N=11</td>
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<td>satisfaction regarding ADL (p=0.027) and independence (p&lt;0.001). Patients reported that eating, drinking, grasping and coordination, dressing/undressing, stretching, and using tools were easier after surgery.</td>
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<td>Population: Mean Age: 49 yr; Gender: males=4, females=7; Injury etiology: Thrombosis=3, Spinal haemorrhage=2, Tumour=2, Syringomyelia=1, Guillain-Barre Syndrome=1, Unspecified=2. Intervention: Data was collected and analysed from patient records who had completed evaluations prior to and after tendon transfer surgery. Surgical procedures included active key pinch by brachioradialis-to-flexor pollicis longus (FPL) transfer (n=10), distal thumb tenodesis (n=10), extensor carpi radialis longus-to-flexor digitorum profundus 2-4 transfer (n=8), intrinsic balancing using either House or Zancolli plasty (n=6), activation of thumb abduction by extensor digit minimi-to-abductor pollicis brevis transfer in (n=3), carpometacarpal joint of thumb, arthrodesis (n=3), posterior deltoïd-to-triceps transfer (n=1), passive key pinch by FPL tenodesis to the radius (n=1). Assessments were conducted at pre-treatment and at 12 mo post treatment.</td>
<td>1. Key pinch strength had improved significantly with means increasing from 0kg at pre-treatment to 1.6kg at 12m post treatment (p&lt;0.05). 2. Grip strength had improved significantly with means increasing from 0kg at pre-treatment to 3.2kg at 12m post treatment (p&lt;0.05). 3. Maximal distance between the thumb and index finger had improved significantly with means increasing from 2.1cm at pre-treatment to 6.4cm at 12m post treatment (p&lt;0.05). 4. Anti-gravity elbow extension was restored in one patient.</td>
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<td>Rothwell et al., 2003 New Zealand</td>
<td>Case Series N_initial=29; N_Final=24</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: 13 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</td>
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<td>Author Year</td>
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<tr>
<td>Welraeds et al., 2003</td>
<td>Belgium</td>
<td>Case Series</td>
<td>N=25</td>
<td></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.</td>
<td>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).</td>
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<tr>
<td>Freehafer 1998</td>
<td>USA</td>
<td>Case Series</td>
<td>N=285</td>
<td></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.</td>
<td>2. 13 out of 285 stated that they were no better, and no patient said they were worse.</td>
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<tr>
<td>Mohammed et al., 1992</td>
<td>New Zealand</td>
<td>Case Series</td>
<td>N=57</td>
<td></td>
<td>1. Subjective Assessment: obtained for 86% of the patients, av. Follow up of 37 mo (range 5-86 mo); 70%</td>
<td>2. 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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</table>

Population: Mean age: 37 yr; Level of injury: C5-C8; Time since injury: 7-356 mo. 
Intervention: Upper limb surgery. 
Outcome measures: Functional testing.

Intervention: Surgical reconstruction. 
Outcome Measures: Self-reported improvement.
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<tr>
<th>Author Year</th>
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<tr>
<td>Ejeskar &amp; Dahllof 1988</td>
<td>Sweden</td>
<td>Case Series</td>
<td>N=43</td>
<td>4: 24; Cu 5: 10; Cu 6: 3; Cu X: 3; tetraplegia. Intervention: Surgery. Outcome Measures: Activities of Daily Living (ADL), Preston Pinch Meter, Hook-grip strength, Elbow extension.</td>
<td>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>Freehafer et al., 1984</td>
<td>USA</td>
<td>Case Series</td>
<td>N=68</td>
<td>Population: Age: 26-70 yr; Gender: males=36, females=7; Level of Injury: 0:1 9 pts; 0:2 2 pts; 0Cu:1 4 pts; 0Cu:2 13 pts; 0Cu:3 9 pts; 0Cu:4 5 pts; 0Cu:6 1 pt. Re-examined 1-14 yr after the last operation. Intervention: Surgery. Outcome Measures: Activities of Daily Living (ADL), Elbow extension, Key grip pinch, Finger flexion.</td>
<td>1. Elbow Extension: 30 elbows in 23 patients; (23/30 with free tendon graft; 7/30 Castro-Sierra and Lopez-Pita method); 5/23 with free tendon graft 1/23 full ext.; 8/23 lack ext. against gravity of max. 60; 10/23 lack even more ext.; 6/7 ext. deficit greater than 60. 2. Key Grip: 50 hands/40 patients; Strength 0-3.5 kg (av. 0.7 kg); 15 cases had minimum of 1.0 kg. 3. Finger Flexion: 14 hand/13 patients (ECRL to profundii II-V); grip 0-0.27 kP (av. 0.13 kP); 5/14 minimum strength 1.0 kg. 4. 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>
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</table>
Discussion
Operative interventions on the hand and upper limb in SCI patients can result in significantly improved pinch force, cylindrical grasp, and the ability to reach above shoulder height. In turn, improved motor function may result in increased ADL task performance and quality of life. Despite the low level of evidence, the subjective acceptance among patients who have had reconstructive surgery is high (Gregersen et al., 2015). Risks of reconstructive surgery include infection, torn attachments, a lengthy recovery and rehabilitation period, and increased need for personal care (Meiners et al., 2002). In addition, many SCI centres do not offer or have access to reconstructive surgery interventions. It has also been debated as to whether surgery is beneficial overall, given the lengthy process of relearning new movement strategies to perform ADLs post-operatively (van Tuijl et al., 2002). More recently, however, reconstructive surgery has been associated with greater satisfaction and ability to perform ADLs (Gregersen et al., 2015).

Conclusions

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

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

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 surgeries increase 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.

Multiple reconstructive surgeries help to improve pinch, grip, and elbow extension functions that improve ADL performance and QOL in tetraplegia.

8.4 Nerve Transfers

Recently, nerve transfers have evolved as an alternative surgical approach to tendon transfers, to improve the functional ability of the hand and upper limb post SCI (Keith & Peljovich 2012). A nerve transfer utilizes a proximal foreign nerve as a donor to re-innervate and repair distal targets (Addas & Midha 2009; Brown et al., 2012; Midha 2004). Traditionally, nerve transfers were performed for brachial plexus injuries. However, more recently the transfer of a nerve branch from the brachialis to the anterior interosseous nerve has been performed for SCI (Hawasli et al., 2015).

Prior to considering surgery, a detailed and careful assessment must be completed. Coulet et al. (2002) recommend assessing the extent of lower motor neuron (LMN) injury and muscle functionality. Lower motor neurons should be assessed to determine the extent of SCI via evaluation of tone, trophic status, deep tendon reflex, joint ROM, deformities, and electrodiagnostic studies. Functional muscle is innervated by supralesional segments, while paralysed and weak muscles may be from upper motor neurons (UMN) or LMN impairments. Following assessment of LMNs and muscle function, priority of functional restoration must be determined. Kozin (2002) recommended restoring elbow extension function first, followed by pinch and finally grasp/release to restore hand function. For nerve transfers around the level of the SCI (lesional level myotomes), surgery should be performed after a re-innervation window of within six months, to prevent significant muscle atrophy from accumulating (Bertelli et al. 2011). However, re-innervation of muscle innervated by an infralesional segment is not time-dependent and can be performed years after injury (Bertelli et al., 2011).

Upon review of the existing literature, six studies investigating the use of nerve transfer for restoration of upper extremity function in tetraplegic patients were identified. The methodological details and results of these studies are presented in Table 25.
Table 25 Nerve Transfer Interventions

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<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>
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<tr>
<td>Fox et al., 2015b</td>
<td>USA Cohort</td>
<td>N=7</td>
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<td>Fox et al., 2015b</td>
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<td>1. Histomorphometric analysis revealed excellent functioning of the transferred nerves.</td>
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<td>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.</td>
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<td>3. No patients experienced a decline in postoperative functioning compared to baseline functioning according to MRC scores.</td>
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<td>4. One patient who underwent deltoid-to-triceps transfer experienced postoperative weakness of the deltoid (MRC grade 4) but eventually subsided and strength returned to baseline levels (MRC grade 5).</td>
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<td>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).</td>
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<td>6. Two patients did not report any changes in functioning from pre-surgery to post-surgery.</td>
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<td>7. 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).</td>
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<td>8. Two patients experienced major complications including urosepsis (n=1) and a urinary tract infection (n=1).</td>
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</table>

<p>| Bertelli et al., 2017 Brazil | Pre-Post | N=9 |                   |         | 1. A recovery of M3 or better in finger flexion strength was observed in 10 out of 17 surgically treated limbs. |
| Bertelli et al., 2017 Brazil |         |     |                   |         | 2. Restoration of finger flexion was observed in four out of eight upper limbs in which the nerve to the brachialis was used; Range of motion was incomplete in all five of these limbs and strength was greater than M3 in all limbs. |
| Bertelli et al., 2017 Brazil |         |     |                   |         | 3. Full finger flexion with M4 strength was observed in all five upper limbs, where the ECRB was transferred to the AIN. |</p>
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<th>Author Year</th>
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<tr>
<td>Bertelli et al., 2015</td>
<td>Brazil</td>
<td>Post-Test</td>
<td>N=7</td>
<td>the brachioradialis was transferred to the AIN. In the remaining five upper limbs, the nerve to the extensor carpi radialis brevis (ECRB) was transferred to the AIN. Outcome measures were assessed at baseline and 16±6 mo.</td>
<td><strong>Outcome Measures</strong>: Manual muscle test (range of finger flexion and strength).</td>
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<td>Fox et al., 2018</td>
<td>USA</td>
<td>Case Series</td>
<td>N=36</td>
<td>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.</td>
<td>1. At time of final postoperative assessment, elbow extension scored BMRC Grade M4 and under full voluntary control in 11 upper limbs (UL) and in 2 UL within same patient, elbow extension scored Grade M3. 2. A BMRC Grade M4 for full thumb extension with wrist in neutral was observed in 8 UL and 4 hands had thumb extension that scored M3. 3. Full metacarpal extension scoring M4 was demonstrated in 12 hands. 4. Finger extension scoring M3 with only partial range of motion at the metacarpal phalangeal joint was observed in the remaining 1 limb. 5. All patients improved at self-transferring and controlling their wheelchairs. 6. After surgery, all patients extended their thumb and fingers without restriction, no decreased function at donor sites and no patient lost abduction strength or shoulder range.</td>
<td><strong>Outcome Measures</strong>: EDX data.</td>
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<tr>
<td>Simcock et al., 2017</td>
<td>New Zealand</td>
<td>Case Series</td>
<td>N=53</td>
<td>Population: &lt;1 yr post SCI: Mean age=36.1±16 yr; Gender: males=7, females=2; Time since injury: &lt;1 yr; Level of injury: not reported; Severity of injury: not reported. &gt;1 yr post SCI: Mean age=38.8±17 yr; Gender: males=22, females=5; Time since injury: &gt;1 yr; Level of injury: not reported; Severity of injury: not reported.</td>
<td>1. Although no statistics were reported, a substantial number of patients presenting years after SCI are candidates for nerve transfers based on EDX data.</td>
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1. Nerve transfer within 3 to 12 mo of injury provides active hand opening for patients following cervical SCI. 2. Neurological assessment identifies patients who may benefit from nerve transfers.
### Fox et al., 2015c

**USA**  
**Case Series**  
**N=9**

| **Intervention:** No intervention. Case note review of medical records from 2007 to 2012 to identify patients that may benefit from nerve transfer surgery. Outcome measures were assessed at six wk, 12 wk and one yr following injury.  
**Outcome Measures:** Neurological assessment. | transfer surgery to improve hand opening. |
|---|---|
| **Population:** Mean Age: 32.9 yr; Gender: males=7, females=1.  
**Intervention:** Data was collected on patients who had received nerve transfer surgery and had been followed-up over a period of 12 mo. 20 surgeries were performed which included Brachialis (BR) to the anterior interosseous nerve (AIN; n=7), BR to the flexor carpi radialis (FCR; n=3), deltoid-to-triceps (n=3, 15%), BR to the AIN/flexor digitorum superficialis (FDS; n=1), BR to the FDS/FCR (n=1), BR to the AIN/FCR (n=1), BR to extensor carpi radialis (n=1), supinator to extensor carpi ulnaris (n=1), supinator to posterior interosseous nerve (n=1), and exploratory surgery (n=1). Assessments were conducted every 3 mos until 12 mos post-surgery.  
**Outcome Measures:** Functional gain self-reports by patients, Medical Research Council elbow flexion grade (MRC), Complications post-surgery. | 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). |

### Discussion

Restoration of upper extremity function in individuals with SCI is helpful to complete many activities of daily living including the ability to perform pressure relief maneuvers, push a manual wheelchair, reach for items and objects above shoulder height and to complete functional transfers. Nerve transfer surgery has emerged as a promising technique for restoration of upper extremity function after SCI, which has many advantages over traditional tendon transfers.

To date, a small number of studies have been published that focus on nerve transfer surgery. Despite this, nerve transfer appears to be a relatively safe and effective surgical alternative to tendon transfer. It has many advantages over tendon transfers, including: no need to wait for neurologic stability, minimal compromise of donor nerve, quicker recovery post operatively, many more surgical options. Fox and colleagues (2015b) found that the risk of post operative decline is low, and the majority of patients report improvements in upper extremity function across a variety of different nerve transfer procedures. Additionally, one study found that regardless of timing (<1 or >1 yr post injury), nerve transfer surgery is effective in restoring hand function (Simcock et al., 2017; Fox et al., 2018). Most importantly, all studies that investigated functionality and grasp strength reported beneficial outcomes in the majority of patients; however, not all patients have
successful surgical outcomes. In this sense, candidates for nerve transfer surgery should be carefully selected. Regardless, the ability of nerve transfers to restore upper extremity function in the majority of SCI patients is quite promising and has the potential to impact patient quality of life, as well as independence. Future research should focus on determining the optimal timing for surgery and outcome after a combination of treatments (e.g., tendon and nerve transfer).

Conclusions

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

There is level 4 evidence (from one pre-post and one post-test study; Bertelli et al., 2017; Bertelli et al., 2015) that nerve transfer surgery can increase motor hand function without compromising donor site function in patients with SCI.

There is level 4 evidence (from one case series; Fox et al., 2018) that patients presenting years after SCI are eligible candidates for nerve transfer surgery.

There is level 4 evidence (from two case series; Simcock et al. 2017; 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.

Nerve transfer surgery to restore hand and upper limb function in SCI patients is a viable alternative to tendon transfer in acceptable candidates.
Individuals with SCI experience a wide range of secondary complications including pain, urinary tract infections, bowel problems and spasticity. Unfortunately, standard medical care is not always successful in managing these complications (Pannek et al., 2015). As a result, many patients turn to complementary and alternative medicines (CAMs) (Pannek et al., 2015). In a recent study, it was found that 19.1% of SCI patients had used CAM, with pain being the most common reason for use (86.4%) (Carlson et al., 2006).

Acupuncture is an ancient Chinese therapy that has been practiced for more than 4000 years to prevent and treat diseases (Lee & Liao 1990; Fan et al., 2018). When a patient undergoes acupuncture, a hair-thin needle is inserted into an acupoint and manipulated manually or electrically (Fan et al., 2018). To date, more than 361 acupoints, which form a network of 14 channels (meridians) have been identified. It has been speculated that acupuncture therapy, when applied to acute SCI, assists in minimizing cord shrinkage and spares ventral horn neurons (Politis & Korchinski 1990; Ran et al., 1992; Tsay 1974; Wu 1990). However, there are few clinical studies to support the therapeutic efficacy of acupuncture in SCI.

Trager psychophysical integration (Trager) is a form of bodywork and movement re-education developed by Milton Trager. It is based off the theory that the brain, through the nervous system, contributes to pain by maintaining muscles and other soft tissues in a chronically contracted and inflamed position (Dyson-Hudson et al., 2001). Trager therapy aims to induce relaxation and release tension through the use of gentle, rhythmic, non-intrusive movements and touch. Patients are taught to identify and correct movement patterns that may lead to pain and as a result it is often considered a form of movement re-education (Dyson-Hudson et al., 2001). Interestingly, several case studies found Trager improves range of motion and decreases pain in a number of musculoskeletal disorders (Blackburn, 2003). However, there are few clinical studies reporting the therapeutic efficacy of Trager in SCI.

The methodological details and results from two studies investigating acupuncture and Trager as a rehabilitative therapy for spinal cord injured individuals are listed in Table 26.
<table>
<thead>
<tr>
<th>Author Year Country Research Design Score Total Sample Size</th>
<th>Methods</th>
<th>Outcome</th>
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<tr>
<td><strong>Dyson-Hudson et al., 2001 USA RCT PEDro=7 N=21</strong></td>
<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 <em>p</em>&lt;0.001 and Trager <em>p</em>=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 (<em>p</em>&lt;0.05) 3. There was a significant effect of time for both acupuncture and Trager groups for average pain &amp; most severe pain (<em>p</em>&lt;0.01, <em>p</em>&lt;0.001 respectively), for the least severe pain the acupuncture group showed a significant reduction (<em>p</em>&lt;0.01) compared to the Trager group. 4. Verbal response scores- there was a statistically significant treatment effect for both groups (<em>p</em>=0.001).</td>
</tr>
<tr>
<td><strong>Wong et al., 2003 Taiwan RCT PEDro=5 N=100</strong></td>
<td><strong>Population:</strong> Mean age: 35 yr; Gender: males=80, females=20; Level of injury: paraplegia=63, tetraplegia=37; Severity of injury: AIS A-B; Chronicity: acute. <strong>Intervention:</strong> 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. <strong>Outcome Measures:</strong> ASIA Impairment Scale (AIS) (sensory + motor), Functional Independence Measure (FIM).</td>
<td>1. Acupuncture group - sensory, motor + FIM scores improved significantly day of D/C + one yr after injury (<em>p</em>&lt;0.05). Control group - only motor score significant improvement at 1yr post injury F/U <em>p</em>=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 <em>p</em>&lt;0.05. 3. More patients in acupuncture group improved to AIS grade B + C or better at D/C + one-yr post <em>p</em>&lt;0.05.</td>
</tr>
</tbody>
</table>
Upon review of the literature, there are very few studies which investigate the use of CAM within the SCI patient population. Wong et al. (2003) investigated the neurologic and functional recovery of acute traumatic SCI patients when treated with electrical acupuncture. They found significant improvements in AIS and FIM scores upon discharge from the hospital and one year after injury in the acupuncture group. Although, an inherent bias may have been present as the reviewer who assessed the participants was not blinded to the group assignment.

Dyson-Hudson et al. (2001) found that traditional acupuncture therapy was no more effective than Trager for the treatment of shoulder pain. This suggests that traditional acupuncture and Trager therapy may be used interchangeably depending on patient preference.

To date, the only CAM techniques that have been evaluated in the SCI population are acupuncture and Trager; however, these studies do not provide conclusive evidence of effectiveness. As the most common reason for CAM use is dissatisfaction with conventional medicine for treatment of pain, it is important to find a therapy which is safe and efficacious. In order to do this, more research is necessary. Future research should focus on determining the long-term effects of acupuncture therapy, as well as functional and neurological outcomes in larger clinical trials.

**Conclusions**

*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 2 evidence (from one randomized controlled trial; Wong et al., 2003) that use of concomitant auricular and electrical acupuncture therapy may improve the neurological and functional recovery of acute spinal cord injured individuals.*
Acupuncture and Trager therapy may reduce upper limb pain post-SCI, however, there is limited evidence that acupuncture improves neurological and functional recovery in SCI.

10.0 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 neuroprostheses. 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, in an effort to establish objective, reliable and measurable outcomes. Other areas for further research have been identified throughout the chapter.

There is level 1a evidence (from one randomized controlled trial; Trumbower et al. 2017) that acute intermittent hypoxia combined with daily hand opening practice significantly improves hand opening in some, but not all, aspects of hand function.

There is level 1b evidence (from one randomized controlled trial; Nightingale et al. 2018) that six weeks of home-based upper-body exercise improves aspects of health-related quality of life.

There is level 2 evidence (from one randomized controlled trial; Hicks et al., 2003) that physical capacity continues to improve 1 - year post discharge and is correlated to a decrease in stress, pain, and depression.

There is level 2 evidence (from one prospective controlled trial; Haisma et al. 2006) that physical capacity (strength and respiratory function) improve during and after inpatient rehabilitation.

There is level 4 evidence (from one pre-post study; Gant et al. 2018) that multi-modal exercise improves muscle strength and function in individuals with SCI.

There is level 4 evidence (from one pre-post study; Hoffman et al. 2017) that weekly activity-based hand therapy is feasible and efficacious at increasing hand task performance in individuals with SCI.

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

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

There is level 4 evidence (from one pre-post test; Portnova et al. 2018) that wearing a wrist driven orthoses as an assistive device may improve hand function and grasp strength.

There is level 1b evidence (from two randomized controlled trials; Yeo et al., 2018; Rice et al., 2014) that education improves wheelchair skills.

There is level 2 evidence (from one randomized controlled trial; Curtis et al., 1999) that education about shoulder exercises reduces the intensity and duration of shoulder pain post SCI.

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 movement time and variability performance.

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 2 evidence (from one prospective controlled study; Frullo et al. 2017) that subject-adaptive upper extremity robotic exoskeleton therapy is feasible, however, no gains in arm function were observed.

There is level 4 evidence (from one pre-post study; Capello et al. 2018) that use of a fabric-based soft robotic glove significantly improves hand function when completing activities of daily living in individuals with SCI.

There is level 4 evidence (from one pre-post study; Kim et al. 2017) that the GRIPIT exoskeleton quantitatively and qualitatively improves writing when compared to conventional pen holders, although it is more difficult to wear.

There is level 4 evidence (from two pre-post studies; Backus et al., 2014; Cortes et al., 2013) that an end effector robotic device can be safely used in patients with tetraplegia to significantly improve upper limb function.

There is level 4 evidence (from one post-test study; Tigra et al., 2018) that an end effector robotic device may improve hand grasping function in individuals with SCI.

There is level 4 evidence (from two case series; Popovic et al., 1999; Prochazka et al., 1997) that the Bionic Glove increases motor and upper limb function in individuals with SCI.

There is level 1b evidence (from one randomized controlled trial; Osuagwu et al. 2016) that BCI-FES should be considered as a therapeutic tool rather than solely an assistive device,
as combined BCI-FES therapy results in better neurological recovery and muscle strength than FES alone.

There is level 2 evidence (from two prospective controlled trials; Athanasiou et al. 2017; Pfurtscheller et al. 2009) that robotic control of a wireless or EEG controlled BCI is possible in SCI patients, however, multiple training sessions and tailored BCI algorithms are needed to improve performance.

There is level 4 evidence (from one pre-post test; Foldes et al. 2015) that a MEG based BCI may provide realistic, efficient and focused neurofeedback in SCI patients to promote neuroplasticity.

There is level 4 evidence (from one pre-post test; Pedrocchi et al. 2013) that the MUNDUS platform may provide functional assistance in activities of daily living to patients with SCI.

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

There is level 2 evidence (from one randomized control trial; 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 two pre-post tests; Kilgore et al., 2018 and Kilgore et al., 2008) that a surgically implanted neuroprosthesis significantly improves grip strength/pinch force to enhance hand function and ADLs in individuals with SCI.

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 neuroprosthesis, individuals with SCI may regain grasp, hold and release abilities.

There is level 4 evidence (from eight case series; Mulcahey 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 one case series; Mangold et al., 2005) that the ETHZ-ParaCare neuroprosthesis is flexible (non-surgical) and has significant positive outcomes in rehabilitation and the ability to perform daily living tasks.

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 2 evidence (from one randomized control trials; Klose et al., 1993) that the addition of NEMS does not improve patient scores in rehabilitation more than physical exercise alone.

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 1a evidence (from one crossover RCT; Gomes-Osman & Field-Fote 2015 that TENS and tDCS, when combined with functional task practice improves aspects of hand-related function.

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 controlled trial; Gomes-Osman et al., 2017) that peripheral sensory stimulation combined with functional task practice improves grip force in individuals with SCI.

There is level 4 evidence (from one pre-post test; Gad et al., 2018) that transcutaneous spinal cord stimulation combined with hand grip training significantly improves hand function.

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 1b evidence (from two randomized controlled trials; Harvey et al., 2017; Popovic et al., 2006) that FES has no added benefit over conventional therapy.

There is level 2 evidence (from one randomized controlled trial; Iwahashi et al., 2017) that therapeutic electrical stimulation has no effect on upper extremity motor function.

There is level 2 evidence (from two randomized controlled trials; Zoghi and Galea, 2017; Hoffman & Field-Fote 2013) that FES in combination with intensive hand task training improves upper extremity motor function.

There is level 2 evidence (from one prospective controlled trial; Hodkin et al., 2018) that multiple FES sessions improves upper extremity motor function.

There is level 1a evidence (from one randomized controlled trial; Gomes-Osman & Field-Fote 2015) that pinch strength significantly improves with vibration therapy but this does not translate to improvements in functional outcomes.
There is level 4 evidence (from one pre-post study; Backus et al., 2014) that an end effector utilizing muscle vibration can be safely used in patients with tetraplegia to significantly improve upper limb function.

There is level 1b evidence (from one randomized controlled trial; Tolmacheva et al., 2017) that TMS combined with PNS significantly improves muscle function of the hand.

There is level 1b evidence (from one randomized control trial; Gomes-Osman & Field-Fote, 2014) that rTMS may reduce corticospinal inhibition and enhance clinical/functional outcomes for several weeks after treatment.

There is level 2 evidence (from two prospective controlled trialz; Bunday et al., 2018; Bunday et al., 2014) that PCMS applied during voluntary activity may enhance spinal plasticity after SCI.

There is level 2 evidence (from one prospective controlled trial; Peterson et al., 2017) that TMS delivered to the motor cortex after elbow extension reconstructive surgery significantly improves elbow extension.

There is level 4 evidence (from one pre-post study; Belci et al., 2004) that TMS may lower intracortical inhibition and improve clinical motor scores.

There is level 1b evidence (from one RCT; Cortes et al., 2017) that a single session of tDCS significantly improves hand grasp in patients with chronic SCI, however, larger clinical trials are necessary to determine the effectiveness of tDCS as a long-term rehabilitation strategy.

There is level 2 evidence (from one cohort study; Potter-Baker et al., 2018) that tDCS paired with massed practice training may provide some advantage in improving the strength of proximal/hand muscles, however, larger clinical trials are necessary.

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 2 evidence (from one prospective controlled trial; Coulet et al., 2018) that active key pinch CMC reconstructive surgery increases key pinch strength when compared to passive key pinch reconstructive surgery.

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 and one pre-post test; Mohindra et al., 2017; 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 also report high satisfaction with their surgical 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 test; Medina et al., 2017) that biceps-to-triceps transfer significantly improved upper extremity functional outcomes in individuals with SCI.

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 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 one pre-post study; Friden et al., 2012a) that multiple reconstructions can improve key-pinç and grip strength.

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; Fox et al., 2015b) that the risk of negative outcomes for nerve transfer surgery, such as postoperative decline compared to baseline, are low.

There is level 4 evidence (from one pre-post and one post-test study; Bertelli et al., 2017; Bertelli et al., 2015) that nerve transfer surgery can increase motor hand function without compromising donor site function in patients with SCI.

There is level 4 evidence (from one case series; Fox et al., 2018) that patients presenting years after SCI are eligible candidates for nerve transfer surgery.

There is level 4 evidence (from two case series; Simcock et al. 2017; 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.
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There is level 2 evidence (from one randomized controlled trial; Wong et al., 2003) that use of concomitant auricular and electrical acupuncture therapy may improve the neurological and functional recovery of acute spinal cord injured individuals.

References


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Abbreviations

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