SCIRE

SPINAL CORD INJURY REHABILITATION EVIDENCE

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.

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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.
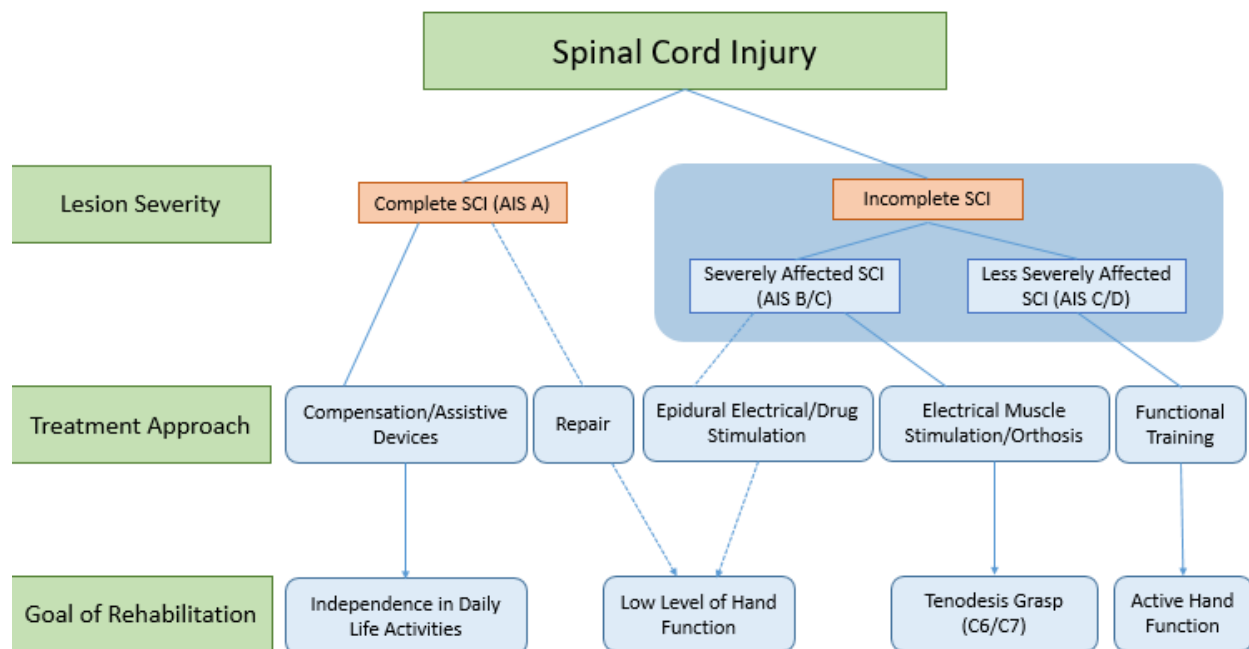
Adapted from Dietz & Fouad, 2013.

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 determing 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 compliment virtual reality intervention, and (3) efficacy of virtual reality systems and types of exercises included.
- Future research should focus on determing 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 require 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 Tuijl 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; Consotrtium 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 nerurorehabilitation, 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

Adopted from: https://assets.nhs.uk/prod/images/A_0518_wheelchair_weights_JRCAK8.a48bd3b1.fill-640x229.jpg

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

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
Trumbower et al., 2017 USA RCT – Crossover PEDro=9 N=6	**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.	1. Daily AIH and hand opening practice improved hand dexterity, function and maximum hand opening in all participants but was not statistically significant (p>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>0.05), however, all participants reduced their JTHF score after daily AIH and hand opening practice versus controls.

		4. Maximum hand opening versus baseline significantly improved with AIH and hand opening practice when compared to controls (p=0.030).
Nightingale et al., 2018 U.K. RCT PEDro=7 N=21	**Population:** 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. **Intervention:** 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. **Outcome Measures**: Physical and mental component scores (PCS and MCS); Health related quality of life (HRQOL); Fatigue; Global fatigue (FSS); WUPSI.	1. The exercise intervention group significantly improved PCS and MCS (p=0.017) and FSS (p=0.036) outcomes in relation to controls. 2. No statistically significant difference was observed in fatigue and WUPSI between groups(p>0.05).
Hicks et al., 2003 Canada RCT PEDro=5 $N_{Initial}$=34; N_{Final}=11	**Population:** Age: 19-65 yr; Level of injury: C4-L1; Severity of injury: AIS A-D; Time since injury: 1-24 yr. **Intervention:** Experimental group (EX) participated in progressive exercise training twice weekly for nine mo-each session offered on alternative days lasing 90-120 min. **Outcome Measures:** Perceived stress scale, Muscle strength, Depression, Physical self-concept pain, Perceived health, Quality of Life (QoL).	1. Overall 11 in the EX group (exercise adherence 82.5%) and 13 in the control group completed the study. 2. No differences were noted between the two groups at baseline. 3. Following training, EX group had significant increases in sub maximal arm ergometry power output (81%; p<0.05) and significant increases in upper body muscle strength (19-34%; p<0.05). 4. EX group reported less pain, stress and depression after training + scored higher than CON in indices of satisfaction with physical function, level of perceived health + overall quality of life (p<0.05).
Haisma et al., 2006 Netherlands Prospective Cohort $N_{Initial}$=186; N_{Final}=42	**Population:** Mean age: 40 yr; Gender: males=140, females=46; Level of Injury: paraplegia, tetraplegia; Severity of injury: complete=125, incomplete=61; Mean time since injury: 105 d. **Intervention:** Assessments were taken at four time points: start of inpatient rehabilitation; three months later; discharge and at one year after discharge. **Outcome Measures:** Power output (PO) peak, VO_2 peak, strength of upper extremity, respiratory function.	1. Age was related to the PO peak and handheld dynamometry (HHD) score (p<0.05), the older the subject the more improvement in either of these measures was significantly less than it was in younger subjects. 2. Men had greater PO peak, VO_2 peak and HHD score than women did (p<0.05), thus improvement in men was greater than women. 3. In tetraplegia subjects the PO peak, VO_2 peak, muscle strength and % of forced vital capacity (FVC) was lower (p<0.05) than it was in paraplegia subjects, but tetraplegia subjects improved more in muscle strength and

		% of forced expiratory flow (FEV1). 4. Those with a complete lesion had greater HHD score and lower % of FVC than those with incomplete lesions (p<0.05).
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: AISA 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: AISA 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 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.

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

3.2 Orthoses

Adopted from: https://www.forcemedic.com/wp-content/uploads/2018/03/therapie-de-la-main-hand-therapy.png

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

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
Harvey et al., 2006 Australia RCT PEDro=8 N$_{Initial}$=44; N$_{Final}$=43	**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.	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.

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
DiPasquale-Lehnerz 1994 USA RCT PEDro=4 $N_{Initial}$=13; N_{Final}=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).

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

DiPasqual et al. 1994; Positional Orthoses

	SMD (95% C.I.)
JTFHT - Writing	2.61 (0.83,4.40)
JTFHT - Turning Cards	2.73 (0.91,4.55)
JTFHT - Small common objects	1.08 (-0.33,2.48)
JTFHT - simulated feeding	2.62 (0.83,4.40)
JTFHT - picking up checkers	1.99 (0.38,3.59)
JTFHT - lifting large light objects	1.79 (0.24,3.34)
JTFHT - lifting large heavy objects	2.12 (0.48,3.76)

-2   -1.5   -1   -0.5   0   0.5   1   1.5   2
Favours Control   SMD (95%C.I.)   Favours Treatment

| 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, Portnova 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-Sluga and Steiger's review (2004).

Future research should focus on determing 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; Portnova 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 Interventions

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
Yeo et al., 2018 Korea RCT PEDro=7 N=24	**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).
Rice et al., 2014 USA RCT PEDro=8 N=93	**Population:** *Intervention Group (IG; n=12):* Mean age: 33.2±14.3 yr; Gender: males=9, females=3; Level of injury: paraplegia=12, tetraplegia=0; AIS level: A=6, B=1, C=3, D=1, Not rated=1.	1. In wheel chair set-up, no significant interaction, between-subject differences, or within subject differences were found between study 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.	2. Although differences were not significant, the percentage of IG participants within the guideline recommendation increased by 25% while the percentage of SCG participants within the guideline recommendation decreased by 5%. 3. No significant differences were found between groups in wheelchair selection (p>0.05); however, 100% of the IG participants had an ultralight MWC at 6mon and 1 yr compared with 68.8% (6 mon) and 77.8% (1Y) of the SCG participants. 4. IG propelled with a significantly lower push frequency than the SCG on tile (p<0.02) and on a ramp (p<0.03) but not carpet (p=0.10). 5. No significant differences were found between NRS or WUSPI scores in the IG and SCG (p>0.05). 6. A simple main effect trend (p=0.07) found that the IG had an increase in the CHART physical subsection scores between 6-mon and 1 yr and an increase in the occupational subsection scores between 6 mon and 1 yr (p=0.07).
	Effect Sizes: Forest plot of standardized mean differences (SMD±95%C.I.) as calculated from pre- and post-intervention data. Rice et al. 2014; Education vs. Standard therapy services (Propulsion - Tile, Propulsion - Carpet, Propulsion - Ramp, NRS, WUSPI) Standardized Mean Difference (95%CI) Favours Control — Favours Treatment	
Curtis et al., 1999 USA RCT PEDro=5 N=42	**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.	

Curtis et al. 1999; Shoulder Exercises

WUSPI — 0.44 (-0.17, 1.05)

PC-WUSPI — 0.47 (-0.14, 1.09)

Standardized Mean Difference (95%C.I.)
Favours Control — Favours Treatment

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 uses may be effective in improving wheelchair skills and preventing shoulder pain.

3.4 Motor Imagery
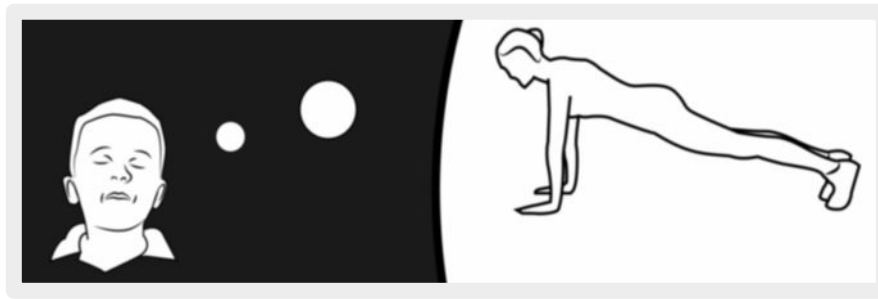
Motor imagery is defined as a cognitive process, in which a person imagines rehearsing a task without performing the physical movement (Scandola et al., 2017). Neuroimaging studies have demonstrated that motor imagery produces similar patterns of neural activation to those of motor execution, particularly 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

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
Di Rienzo et al., 2015 France Pre-Post N=8	**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).	1. No statistically significant differences between groups on KVIQ scores or sub-scores (all p>0.05). 2. MT were greater in SCI participants during the first pretest compared to the third pretests of the design (p<0.01) but not in HC (p>0.05). 3. In SCI participants, post-test MV was superior to the median pretest value (p<0.05), but not in HC (p>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<0.01) but not in HC (p>0.05).

		6. MV was statistically predicted by the number of SAM rouces activated during MI in the SCI group (p<0.001) but not in HC (p=0.32).
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 (HP) 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 prescence 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 a., 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 Articles

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
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-asychronous (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-asychronous (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.

| | Questions (ICQ), Big-Five Inventory (BFI-10), Tellegen Absorption Scale (TAS). | |

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

Adopted from: https://cdn.shopify.com/s/files/1/0238/0391/files/013_toyra_rehabilitation_grande.jpg?v=1505765341

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

Author Year Country Research Design PEDro Score Sample Size	Methods	Outcomes
Prasad et al., 2018 India RCT PEDro=7 N=22	**Population:** *Virtual reality and occupational therapy:* 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. *Occupational therapy:* 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. **Intervention:** 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. **Outcome Measures**: CUE; BBT; SCIM.	1. No significant difference in hand function were observed between the groups for all outcome measures (p>0.05).
Dimbwadyo-Terrer et al., 2015 Spain RCT PEDro=6 N=31	**Population:** *Conventional therapy and a virtual reality program:* 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. *Conventional therapy:* 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. **Intervention:** 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. **Outcome Measures**: MMT; FIM; SCIM III; BI; MB; MI.	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.
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

	Outcome Measures: Dexterity; Coordination and grip functions; Kinematic and functional parameters.	functional status were observed between groups (p>0.05).
Dimbwadyo et al., 2015 Spain PCT N=9	**Population:** *Intervention:* 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. *Control:* Mean age=44.2±22.9 yr; Gender: males=2, females=1; Time since injury: 5 mo; Level of injury: T4=2, T6=1; Severity of injury: AISA A=3. **Intervention:** 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. **Outcome Measures**: MB; BI; SCIM; NHPT; JHFT.	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.
Seanez-Gonzalez et al., 2016 USA Pre-Post N=5	**Population:** 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. **Intervention:** Participants performed five visu-spatial 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. **Outcome Measures:** MMT; Isometric force; Beck Depression Inventory (BDI); FIM; Fractional anisotropy (FA).	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>0.05). 4. Motor training significantly increased FA, indicating localized white matter microstructure changes (p=0.03).
Dimbwadyo et al., 2015 Spain Pre-Post N=15	**Population:** 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. **Intervention:** Participants received daily conventional therapy complemented with virtual reality ADL training. Outcome measures were assessed at baseline and 4 wk. **Outcome Measures** SCIM; ROM.	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<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<0.05). 3. No significant difference was observed pre and post assessment for the comb exercise (p>0.05).
Foldes et al., 2015 USA Post Test N=3	**Population:** 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. **Intervention:** 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	1. Overall grasp success rates varied between 62 and 64% with success rate significantly better than chance for each patient (p<0.001). 2. Although grasp success rates improved after breaks between trials, the success rate was not significantly different when

	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 1min 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.	compared to trials before breaks (p=0.22). 3. Success rates were also significantly greater than chance during grasp-only and rest-only trials (both p<0.001). 4. Two patients demonstrated a significant increase in their ability to modulate their SMRs by 14.9pp and 15.0pp (both p<0.05) from baseline to post-treatment. The remaining patient did not exhibit any significant improvement in modulating SMRs. 5. ANOVA analyses revealed a significant interaction between patient and session-segment (p<0.001) and a significant main effect of session-segment (p<0.001). 6. Patients took an average of 1.96sec to complete a successful grasp, indicating that grasping using SMRs had been learnt quickly.
Robinson et al., 2014 UK Post-Test N=10	**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. **Intervention:** Aiming movements were performed in two directions (20 cm away or toward), with or without vision with a ball transfer unit by both SCI patients and age-matched neurotypical controls. Trials that contained a sub-movement phase (i.e., discontinuity in velocity, acceleration or jerk) were identified. **Outcome Measures:** Kinematic variables, Frequency and distribution (velocity, acceleration or jerk discontinuity), Amplitude and duration of sub-movements.	1. 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).

			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).
Scott & Vare 2015 Australia Post Test N=16	**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. **Intervention:** 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). **Outcome Measures:** Absolute performance on task matching (time to complete (TTC)), Efficacy of completion on task matching (integral of the error (IOE)), Ability to issue appropriate commands using the virtual hand (percentage of errors (POE)).		1. The non-injured participants had significantly faster TTC scores than the SCI participants on completing Targets 3 and 4 (p>0.05).
			2. Additionally, high cervical participants were found to have significantly slower TTC scores than the mid cervical group (p<0.05).
			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<0.05).
			4. Non-injured participants had a significantly lower POE than those with SCI in completing Targets 3 and 4 (p<0.05).
			5. On examination of TTC, IOE and POE for Targets 5 and 6, no significant differences were found between SCI and non-injured participants (p>0.05).
			6. There was a significant increase in the TTC for Target 8 for SCI participants over non-injured participants (p<0.05).
			7. There was a significant increase in IOE for Target 7 by SCI participants when compared to non-injured participants (p<0.05).
			8. There was a significant increase in the POE commands for Target 7 and Target 8 for SCI participants compared to controls(p<0.05).
			9. Non-injured participants were significantly faster than SCI participants in completing Target 10 (p<0.05), but there was no significant difference between the two groups for Target 9 (p>0.05).
			10. For speeds 1, 2, and 3, TTC scores were significantly lower for SCI participants (p<0.05).

| | | 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

Adopted from: https://exoskeletonreport.com/wp-content/uploads/2016/11/NX-A2-close-up.jpg

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 Robatics Interventions

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
Frullo et al. 2017 USA PCT N=17	**Population:** *Assist-as-needed (AAN) robotic controller*: Mean age=53.5 yr; Gender: not reported; Time since injury: 16 yr; Level of injury: C3 – C6. *Subject-triggered (ST) robotic controller:* Mean age=53.5 yr; Gender: not reported; Time since injury: 16 yr; Level of injury: C3 – C6. **Intervention:** 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. **Outcome Measures**: Action Research Arm Test (ARAT); Modified Ashworth Scale (MAS); Grip Pinch Strength assessment (GPS); GRASSP.	1. No significant difference was observed in the ARAT, MAS, GPS, or GRASSP scores or between groups ($p>0.05$). 2. The AAN robotic controller demonstrated gradual improvement in movement quality over the ST robotic controller.
Capello et al. 2018 USA Pre-Post N=9	**Population:** 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. **Intervention:** 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. **Outcome Measures**: Hand function during ADL tasks (Toronto Rehabilitation Institute Hand Function Test (TRI-HFT)); Object manipulation; Lift force.	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 ($p<0.05$). 2. Lift force increased significantly when using the assistive soft robotic glove ($p<0.05$).
Kim et al. 2017 Korea Pre-Post	**Population:** 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

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
N=4	of injury: C5 – C6; Severity of injury: AISA A=2, B=2. **Intervention:** 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. **Outcome Measures**: *Quantitative outcomes:* Accuracy of writing; Solidity of writing; *Qualitative outcomes:* Appearance; Portability; Difficulty of wearing; Difficulty of grasping; Writing sensation; Fatigability; Legibility.	writing than conventional pen holders or with their own hand (p<0.05). 2. Qualitative results showed that GRIPIT has advantages for writing sensation, fatigability, and legibility; Participants found it more difficult to wear than a conventional pen holder; No difference was observed in portability and difficulty grasping (p>0.05).
Backus et al. 2014 USA Pre-Post N=18	**Population:** Mean age: 40.5±13.0 yr; Gender: males=8, females=2; Level of injury: C2-C3=3, C4-C7=7; Mean ASIA motor score: 15.8±3.9; Mean time since injury: 3.0±1.1 yr. **Intervention:** Test effect of assisted movement with enhanced sensation (AMES) using vibration to antagonist muscle to reduce impairments and restore upper limb function in people with incomplete tetraplegia. Two or three sessions over 9-13 wk per participant. **Outcome Measures:** Strength and active motion tests on the AMES device, International Standards for the Neurological Classification of SCI (ISNCSCI) motor and sensory examinations, Modified Ashworth Scale (MAS), grasp and release test (GRT), Van Lieshout Test (VLT), Capabilities of Upper Extremity questionnaire (CUE).	1. No significant change in MAS scores (p=0.371) or ISNCSCI scores (p=0.299 for motor, p=0.459 for sensory-light tough, p=0.343 for sensory-pin prick). 2. Strength test scores increased significantly for MCP extension (p≤0.01) and flexion (p≤0.05) and for wrist extension (p≤0.001) and flexion (p≤0.01). 3. Active motion test scores increased significantly for MCP joints (p≤0.001) and wrist (p≤0.001). 4. Out of GRT, VLT and CUE scores, only GRT scores were significantly improved after training and slightly between post treatment and 3-mo post treatment (p=0.025).
Cortes et al. 2013 USA Pre-Post N=10	**Population:** Mean age: 44.8±16.3 yr; Gender: males=8, females=2; Level of injury: C4-C6=10; Severity of injury: AIS-A complete=3, AIS-B incomplete=4, AIS-C incomplete=1, AIS-D incomplete=2; Mean time since injury: 4.7±2.5 yr. **Intervention:** Chronic tetraplegic SCI patients participated in a 6-wk wrist-robot training protocol (1hr/day, 3 times/wk) to evaluate feasibility, safety and effectiveness on upper limb. **Outcome Measures:** Motor performance, Corticospinal excitability, Upper extremity Motor score (UEMS), Visual Analogue	1. Significant improvements in aim and smoothness (p=0.03). 2. No changes in deviation, mean speed, peak speed and duration of movement was found. 3. No changes in motor strength of trained right arm (p=0.4) or untrained left arm (p=0.41). 4. No significant changes in MAS of either arm (p>0.05 for both). 5. No significant changes in pain levels after training (p=0.99). 6. There were no changes in any neurophysiological parameters after the 6-wks of training (p>0.05).

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
	Scale (VAS), Modified Ashworth Scale (MAS), resting motor threshold (RMT), Motor evoked potential (MEP) amplitude and latency at rest, MEP facilitation.	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.
Tigra et al. 2018 France Post-Test N=5	**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. **Intervention:** Participants piloted a newly developed assistive device (human-machine interface) for hand grip function that utilizes EMG signals from selected muscles to operate a robot hand. **Outcome Measures:** Voluntary muscle contraction (EMG); Hand grasping.	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.
Popovic et al., 1999 Yugoslavia Pre-Post N=12	**Population:** Mean age: 26.5 yr; Level of injury: C5-C7; Severity of injury: complete=10, incomplete=12; Length of experience with device: ≥6 mo. **Intervention:** Subjects utilized a bionic glove to complete functional testing of quantitative and qualitative outcome measures. **Outcome Measures:** Quadriplegia Index of Function (QIF), Functional Independence Measure (FIM), Upper Extremity Function Test, Goniometric Measurements.	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.

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
Prochazka et al., 1997 Canada Pre-Post N=9	**Population:** Age: 22-42 yr; Gender: males=8, females=1; Level of injury: C6-C7; Time since injury: 16 mo–22 yr. **Intervention:** Use of bionic glove. **Outcome Measures:** Mean peak force of tenodesis grasp, Qualitative ratings of manual tasks.	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. 2. Most manual tasks improved significantly with the use of the glove.
Coignard et al. 2013 France Observational N=63	**Population:** *Injury Group (n=29):* Mean age=37.8±13.3 yr; Injury etiology: spinal cord=23, post-stroke locked in syndrome=2, arthrogryposis=1, quadruple amputee=1, cerebral palsy=1, spinal muscular atrophy=1; *Controls (n=34):* Mean age=32.4±11.2 yr. **Intervention:** No intervention. To evaluate the reliability and functional acceptability of the "Synthetic Autonomous Majordomo" (SAM) robotic aid system in a domestic environment using three multi-step scenarios: selection of the room in which the object to be retrieved was located, selection of the object to be retrieved, the grasping of the object itself and the robot's return to the user with the object. **Outcome Measures:** Selection time (time between task's "start" command and room/object selection click), Number of failures, Qualitative questionnaire.	1. No significant difference between scenarios 1 and 2 in room/object selection, validation times and number of failures for controls and patients (p>0.05). 2. Statistically significant difference between scenario 2 and 3 in object selection time for controls and patients (p<0.05) but not for number of object selection failures (p>0.05). 3. Patients took significantly longer to select the room and the object than the controls did (for room selection in scenarios 1 and 3 and for object selection in all three scenarios) (p<0.05). 4. No significant patient versus control differences in the number of failures (p>0.05). 5. Experience of computer use had significantly affected speed of task for patients in scenario 3 (p<0.05) and controls in all scenarios (p<0.05). 6. Overall, the robot was found to be acceptable by both patients and control participants.

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. GThe 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 efficiacy, 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
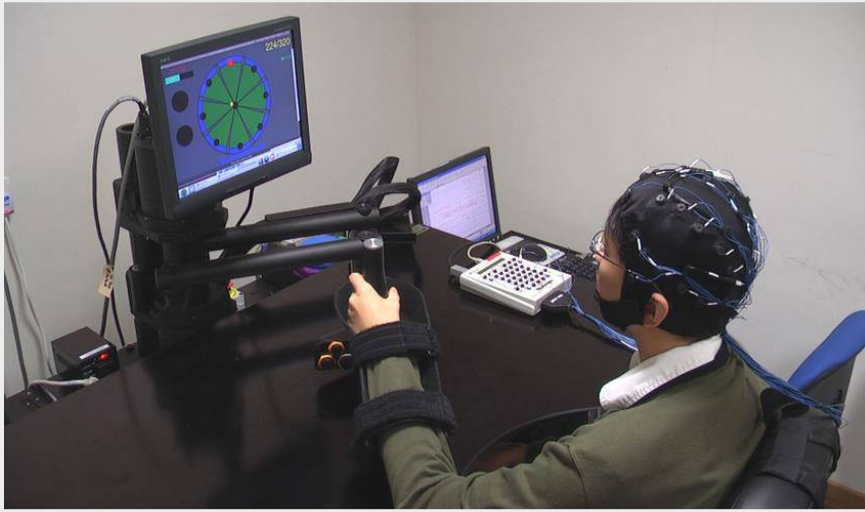
Brain-computer interface (BCI) technology utilizes brain signals instead of spinal or peripheral motor systems to drive external devices (Birbaumer et al., 2006; Collinger et al., 2013). These devices act as assistive technology to help individuals with SCI complete activities of daily living, without 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 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 Inteventions

Author Year Country Research Design PEDro Score Sample Size	Methods	Outcomes
Osuagwu et al., 2016 UK RCT PEDro=6 N=12	**Population:** 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. **Intervention:** 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.	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.

	Outcome Measures: Event related desynchronization (ERD); Somatosensory evoked potential (SSEP); ROM; MMT.	3. SSEP returned in 3 patients in the BCI-FES group, while no significant changes were observed in the FES alone group (p>0.05). 4. 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. 5. MMT significantly improved in all muscles groups in the BCI-FES group (p<0.05), while the FES group improved shoulder muscles or muscles involved in controlling flexion (p<0.05).
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.

	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.	2. User intention was detected with 100% success. 3. Averaging all subjects and tasks, the mean evaluation score was 1.6, with a minimum of 1.13. 4. All users, but one, subjectively perceived the usefulness of the assistance and could easily control the system. 5. Donning time ranged from 6 to 65 minutes.
Blabe et al., 2015 USA Observational N=156	**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 micoelectrode 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 be "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

Adopted from: https://www.medgadget.com/wp-content/uploads/2019/05/fadsfj.jpg

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; Winstein 1991).

The ability to use intrinsic feedback to guide performance is impaired in patients with cognitive and perceptual deficits (Flnn & 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

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
Kohlmeyer et al., 1996 USA RCT PEDro=10 N_Initial=60; N_Final=45	**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.	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.
Klose et al., 1993 USA RCT PEDro=5 N_Initial=31; N_Final=28	**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.	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 ($p<0.05$).

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

Klose et al. 1993; Biofeedback Training

MMS   0.66 (-0.10,1.42)

FAS   0.09 (-0.65,0.83)

-2   -1.5   -1   -0.5   0   0.5   1   1.5   2

Favours Control   Standardized Mean Difference (95%C.I.)   Favours Treatment

| Brucker & Bulaeva 1996 USA | **Population:** Age: 17-63 yr; Gender: males=81, females=19; Level of injury: C2-C6; Time since injury: 1-29.7 yr. | 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 |

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
Kohlmeyer et al., 1996 USA RCT PEDro=10 N_Initial=60; N_Final=45	**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.	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.
Klose et al., 1993 USA RCT PEDro=5 N_Initial=31; N_Final=28	**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.	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 ($p<0.05$).

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

Klose et al. 1993; Biofeedback Training

MMS 0.66 (-0.10,1.42)

FAS 0.09 (-0.65,0.83)

-2   -1.5   -1   -0.5   0   0.5   1   1.5   2

Favours Control   Standardized Mean Difference (95%C.I.)   Favours Treatment

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%

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
Kohlmeyer et al., 1996 USA RCT PEDro=10 N_Initial=60; N_Final=45	**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.	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.
Klose et al., 1993 USA RCT PEDro=5 N_Initial=31; N_Final=28	**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.	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 ($p<0.05$).
	Effect Sizes: Forest plot of standardized mean differences (SMD±95%C.I.) as calculated from pre- and post-intervention data. Klose et al. 1993; Biofeedback Training MMS: 0.66 (-0.10,1.42) FAS: 0.09 (-0.65,0.83) Favours Control — Standardized Mean Difference (95%C.I.) — Favours Treatment	
		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.

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 Dijik 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.

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

4.5 Neuroprostheses

Adopted from: https://3w568y1pmc7umeynn2o6c1my-wpengine.netdna-ssl.com/wp-content/uploads/2019/04/Neuroprosthetic-Limbs-IMG-01.jpg

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

Benefits of Neuroprostheses	Drawbacks of Neuroprostheses
• Induces long term changes within the CNS (Popovic et al., 2002) • Used as a rehabilition system to promote recovery and better hand function as a permanent device • Augment grasp and manipulation functions required for ADLs.	• Technology still being developed • Application is labour intensive • Acceptance of device by patient • Implantation may not be successful • Surgery • Technical and maintenance difficulties • Extensive training • Donning time (if transcutaneous) • Long-term reliability of hand function

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, neuroprotheses 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 Interventions post-SCI

| Kilgore et al., 2018
 USA
 Pre-Post
 N=13 | **Population:** Mean age=37 yr; Gender: males=10, females=3; Time since injury: 5.5 yr; Level of injury: C5 – C6. | 1. Stimulation produced active extension and flexion for all five digits in all 15 arms studied, however, no subject statistics were reported. No subject |

	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. **Outcome Measures**: Active range of motion; Grip strength; Ability to pick up and release objects.	had any active movement in their fingers or thumbs when the stimulation was turned off. 2. There was a significant increase in grip strength when the neuroprosthesis was turned on for all individuals ($p<0.0001$). 3. 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.
Kilgore et al., 2008 USA Pre-post N=3	**Population:** Mean age: 34.0±9.5 yr; Level of injury: C5=1, C6=2. **Intervention:** A second generation neuroprosthesis system was implanted into individuals and functional outcomes were evaluated. **Outcome Measures:** Grasp and Release Test (GRT), Activities of Daily Living Abilities (ADLAT), Craig Handicapped Assessment and Reporting Tool (CHART), NP Usage Survey.	1. Functional Outcomes: all three subjects used their NP to perform activities that they could not perform prior to implantation (post implant follow up ranged from 2-4 yr). 2. Body Structures and Function: every subject improved in pinch force strength; post op pinch force with the NP was significantly greater than without the NP (paired-sample t-test, $p=0.038$). 3. Activities: every subject was able to double the number of objects manipulated in the GRT with NP (two subjects completed 6/6 tasks; one subject 5/6 tasks) 4. ADLAT all three subjects improved in least five activities with one subject in all nine. 5. Participation: all three subjects increased their scores for physical independence, one in the mobility task, one in the social integration scale, one subject a decrease in occupation subscale. 6. Device Usage: 2/3 reported daily usage of the NP; 1/3 used the device 50% of the time.
Peckham et al., 2001 USA Pre-post N$_{Initial}$=51; N$_{Final}$=50	**Participants:** Age: 16-57 yr; Gender: males=42, females=9; Level of injury: C5-C6; Mean time since injury: 4.6 yr. **Intervention:** Participants were trained to use the neuroprosthesis and to use it for functional activities. Once they were satisfied with their ability to perform daily activities or when they reached a plateau in proficiency then rehab was complete. **Outcome Measures**: Pinch strength, active ROM, Grasp-Release Test, Activities of Daily Living (ADL) Abilities Test, ADL Assessment Test & user satisfaction survey.	1. When the neuroprosthesis was activated all participants increased their pinch force in lateral pinch ($p<0.001$) and some increased their pinch force in palmar grasp ($p<0.001$). 2. 98% of participants moved at least one object with the neuroprosthesis ($p<0.001$) and 37 improved by moving at least three more objects ($p<0.001$). 3. Disability was reduced in 49 of 50 participants as measured by the ADL abilities or ADL assessment tools.
Taylor et al., 2001 UK Pre-Post N$_{Initial}$=9; N$_{Final}$=8	**Population:** Age: 31-48 yr; Gender: males=7, females=1; Level of injury: C4-6; Time since injury=43-430 mo; Follow-up time=8-53 mo.	1. No statistical results reported 2. Completion of personal care was provided by outside nursing agencies. (mean 11.5 hr/day, range 3-24 hr); four users had additional

	Intervention: Interviews- reviewing use of Neuro Control Freehand System. **Outcome Measures:** Amount of Care & The System.	care from family members (mean 3.4 hr/day, range 2-5 hr); no users claimed that care given by family members had decreased 3. System-donning external components 5-10 min; most users reported no significant problems fitting the external equipment; two users had problems locating the coil; three locating the shoulder controller; one had persistent problems maintaining the position through the day due to the adhesive tape used becoming detached (four reported this as an occasional problem); four users had problems with skin allergy to the tape or double sided adhesive rings; two users reported that the system made transfers more difficult; three users never stopped using the system due to system failure; some problems with equipment reliability; no change in paid caregiver time; six users felt more confident when using the system; seven felt their quality of life had improved.
Carroll et al., 2000 Australia Pre-post N=6	**Population:** Mean age: 29.1 yr; Gender: males=4, females=2; Level of injury: tetraplegia; Time since injury: 1.2-11.3 yr. **Intervention:** The Freehand System – an implanted multichannel neuroprothesis. **Outcome Measures:** Pinch forces, Grasp and Release Test (GRT), Activities of Daily Living (ADL) Test.	1. There was significant improvement in lateral pinch and palmar grasp force after rehabilitation with and without the neuroprothesis. 2. Force differences were not found between presurgery and rehabilitation without neuroprothesis. 3. With neuroprothesis, subjects could grasp, move and release more items in the 30 sec GRT, as compared to without the neuroprothesis. 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.
Mulcahey et al., 1997 USA Pre-post N=5	**Population:** Age: 16-18 yr; Level of injury: C6=5, Time since injury: >1yr. **Intervention:** Implanted Freehand System. **Outcome Measures:** Grasp Release Test, Activities of Daily Living (ADL).	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).
Mulcahey et al., 2004 USA Case Series N=4	**Population:** Age: 13-16 yr; Level of injury: tetraplegia; Time since injury: 4-16 wk.	1. No statistical results reported. 2. No perioperative complications reported.

	Intervention: The following muscles were implanted with intramuscular electrodes: Extensor digitorum profundus, extensor pollicis longus, flexor pollicis longus, adductor pollicis, and opponens pollicis for each subject. **Outcome Measures:** Muscle Strength-Pinch Force & Hand Function, Performance of Activities of Daily Living (ADL), Satisfaction with + without the Freehand System (Canadian Occupational Performance Measure (COPM)), Upper Extremity Capacity, Quadriplegic Index of Function.	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.
Alon & McBride 2003 USA Pre-Post N=7	**Population:** Gender: males=7, females=0; Level of injury: C5-C6; Mean time since injury: 6 mo. **Intervention:** Subjects practiced with the neuroprothesis daily to regain grasp, hold, and release ability and to restore selected functions of 1 of the 2 paralyzed hands. Subjects were observed 2-3x/wk for 3 wks. **Outcome Measures:** Activities of Daily Living (ADL) tasks, Hand impairment measures (two grasp and release tests).	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<0.05).
Hobby et al., 2001 UK Pre-post N=9	**Population:** Age: 16-55 yr; Level of injury: tetraplegia. **Intervention:** The patients, using an external stimulator, built up the muscles strength in the hand and forearm, to ensure the muscles were in good condition at the time of surgery. **Outcome Measures:** Grip Strength, Activities of Daily Living (ADL).	1. 7/9 use Freehand System daily. 2. Provided an active grip of some strength which allowed many functional activities. 3. Increase in self-confidence. 4. For over 80% of their selected ADL goals, user preferred to be independent with their Freehand system than use previous method or have activity performed by caregiver.
Snoek et al., 2000 Netherlands Pre-Post N_{Initial}=10; N_{Final}=4	**Population:** Age: 20-65 yr; Gender: males=8, females=2; Level of injury: C4 to C6; Classification: 3-Cu=3, 1-O=5, 2-O=1, 0-O=1; Fitted hand: Right n=6, Left n=4. **Intervention:** Training for use of Handmaster. **Outcome Measures:** Not specified.	1. Six people left the study for various reasons (>50%). Over all the four remaining were able to perform several tasks with the Handmaster that they were not able to without it (i.e., 3/4 were able to put the splint on independently).
Mangold et al., 2005 Switzerland Case Series N=11	**Population:** Age: 15-70 yr; Gender: males=9, females=2; Level of injury: C5-C7; Severity of injury: AIS A-D. **Intervention:** FES was carried out with a stationary stimulation system and two portable systems (ETHZ-Paracare FES system, and Complex Motion).	1. Cervical SCI patients can benefit from transcutaneous FES of hand muscles during rehabilitation with respect to muscle strengthening, facilitation of voluntary muscle activity and improvements of ADL functions.

	Outcome Measures: Videos of functional tasks: hand function tests, Self-designed functional tests, Follow-up query-assessment of muscle strength.	2. Surface FES system is more flexible in its application and does not need surgical procedures. 3. High flexibility in electrode placement, stimulation programmes, and FES control devices is required in order to adapt the system to individual needs.
Memberg et al., 2003 USA Case Series N=22	**Population:** Level of injury: C5-C6. **Intervention:** Epimysial or intramuscular electrodes were implanted on the triceps. Following surgery standard stimulation exercise regimens were followed. **Outcome Measures:** Elbow extension moments at different elbow positions, Performance in controllable workspace experiments, Comparison to an alternative method of providing elbow extension in these individuals (posterior deltoid to triceps tendon transfer).	1. Variation in elbow moment across subjects significantly greater than the variance within subjects (ANOVA $p<0.001$). 2. 10/11 elbows tested elbow moment generated by triceps stimulation at different elbow angles, elbow moment weakest with elbow in more extended position (30º flexion) and peaked with elbow at 90º flexion, significant ANOVA $p<0.001$. 3. Elbow moment generated by triceps stimulation at 90º and 120º elbow flexion was significantly greater than elbow moment produced by tendon transfer (ANOVA $p<0.05$), no difference between elbow extension methods at 30º elbow flexion. 4. Triceps stimulation and posterior deltoid together provided a greater elbow moment than each method separately, difference significant at each elbow position $p<0.05$, except at 90º. 5. Quantitative workspace assessment done on 5 arms, more successful with triceps stimulation, significant for each subject, chi square $p<0.05$). 6. Average acquisition time with triceps stimulation less than without stimulation 4/5 arms (3.2-6.4 seconds) and significant in 3/5 arms (unpaired t-test $p<0.01$) and not for one $p=0.076$.
Taylor et al., 2002 UK Case Series N=9	**Population:** Mean age: 38.4 yr; Gender: males=7, females=1; Level of injury: C4-C6; Mean time since injury: 10.1 yr. **Intervention:** Assessment of the Freehand System. **Outcome Measures:** Grasp Release Test, Grip Strength, Activities of Daily Living (ADL), Sensory ability (static 2 pt discrimination).	1. Grasp release test results: increase in the types of tasks that subjects could perform (pre n=1.4) and post implantation (n=5.1 $p=0.011$). 2. One-yr post implantation the types of tasks performed was 5.5 $p=0.027$, without the system it was 1.2 ($p=0.028$). 3. Number of repetitions increased post implantation from 12.7 to 37.4 ($p=0.028$) and without the implant post-implantation (20.2, $p=0.046$). 4. At one-yr number of repetitions was increase to 50.5, $p=0.046$ with the system and without 24.3, $p=0.28$.
Bryden et al., 2000 USA Case Series N=4	**Population:** Age: 23-48 yr; Level of injury: C5-C6. **Intervention:** Participants were implanted with an upper extremity neuroprothesis	1. No statistical analysis was completed. 2. Passive elbow extension was within normal limits.

	including a triceps' electrode to provide stimulated elbow extension. Participants exercised triceps 4-6 hr/session using a programmed electrical stimulation exercise regimen that includes breaks. Participants exercised either nightly or every other night-whatever was best for maintaining an optimal amount of strength. **Outcome Measures**: Five overhead reaching tasks, Amount of assistance required to complete the task, Survey of home use.	3. With stimulated triceps subjects attained full elbow extension; without it full range was not met.
Wuolle et al., 1999 USA Case Series N$_{Initial}$=42; N$_{Final}$=30	**Population:** Age: 13-53 yr; Gender: males=26, females=8; Level of injury: tetraplegia; Follow-up time: 1 yr. **Intervention:** Implemented with a hand neuroprosthesis that provides grasp and release. **Outcome Measures:** Standardized test of grasp and release (GRT), Measurements of pinch strength and range of motion, Satisfaction survey, Activities of Daily Living (ADL) survey.	1. General Satisfaction: 87% were positive agree or strongly agree, 97% would recommend neuroprosthesis to others, 90% were satisfied with neuroprosthesis, 90% stated neuroprosthesis was reliable, 87% would have surgery again, 80% felt the neuroprosthesis met their expectations, & 77% would pay for the neuroprosthesis if they had the money. 2. Life Impact: 88% responses were positive for life impact; 90% stated neuroprosthesis improved their quality of life; 87% positive impact on their life (90% reported did not make a negative impact); 83% provided a benefit ADL; 87% responses regarding changes in ADL were positive; 93% participants could perform ADL easier; 93% could perform ADL such as painting and shaving; 90% had increased confidence when performing ADL; 83% could perform ADL more normally; 73% could perform ADL faster. 3. Independence: 81% of responses were positive; 87% reported they were able to function more independently; 83% used less adaptive equipment; 87% required less assistance from others; 67% felt more comfortable out in the community alone. 4. Occupation: 57% of responses to occupation questions were positive 5. Appearance: 87% felt their hand appearance was unchanged or improved. 6. Usage: used prosthesis median of 5.5 days/wk - ranged from 15 participants (44%) who donned the neuroprosthesis 7day/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

		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. **Outcome Measures:** Grasp force, Grasp-Release Test, Tests of Activities of Daily Living (ADL) (functional independence), Usage Survey.	1. Pinch force ranged from 8 to 25N, with stimulation and greater than tenodesis grasp alone. 2. All demonstrated functional grasp patterns and were able to manipulate at least three more objects with the neuroprosthesis; had increased independence and were able to use the neuroprosthesis at home on a regular basis; the implanted stimulator proved to be safe and reliable.
Smith et al., 1994 USA Case Series N=5	**Population:** Age: 13-19 yr; Gender: males=5; Level of injury: C5-C6; Time since injury: 3-72 mo. **Intervention:** Intramuscular electrodes were implanted in the upper extremity muscles (Freehand System). **Outcome measures:** Breslow test.	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.
Smith et al., 1996 USA Case Series N=5	**Population:** Age: 13-19 yr; Gender: males=3, females=2; Level of injury: C5=5; Time since injury: 3-72 mo. **Intervention:** Implanted Freehand System and tendoesis. **Outcome Measures:** CWRU Hand System (Case Western Reserve University), Grasp and Release Test.	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<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).

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 wide spread 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 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.

5.0 Sensorimotor Stimulation Interventions
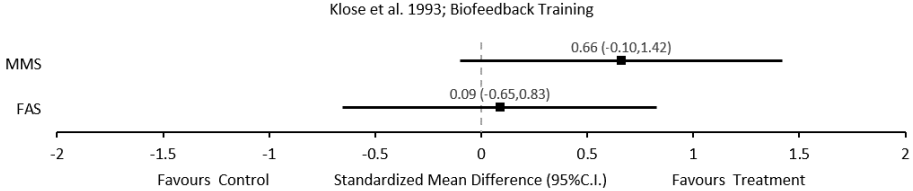
5.1 Neuromuscular Electrical Stimulation

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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

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
Needham-Shrophire et al., 1997 USA RCT PEDro=8 $N_{Initial}$=43; N_{Final}=32	**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 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. 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 or more muscle grades after four weeks of NMS cycling compared with Group 3 (p<0.003). 3. Following the second four weeks of training, a significant difference was found between Groups 1 and 3 (p<0.0005) and between Groups 2 and 3 (p<0.03). 4. No statistical difference was found between Groups 1 and 2 (p=0.15).
Klose et al., 1993 USA RCT PEDro=5 $N_{Initial}$=31; N_{Final}=28	**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.	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).

	Outcome Measures: Manual muscle test, Functional activities score.	
	Effect Sizes: Forest plot of standardized mean differences (SMD±95%C.I.) as calculated from pre- and post-intervention data. Klose et al. 1993; Biofeedback Training MMS 0.66 (-0.10,1.42) FAS 0.09 (-0.65,0.83) -2 -1.5 -1 -0.5 0 0.5 1 1.5 2 Favours Control Standardized Mean Difference (95%C.I.) Favours Treatment	
Cameron et al., 1998 USA Case Series N=11	**Population:** Age: 18-45 yr; Gender: males=10, females=1; Level of injury: C4-C7; Time since injury: >1 yr. **Intervention:** Testing of hybrid device, eight weeks of Neuromuscular Stimulation (NMS) assisted exercise with training sessions three times per week. **Outcome Measures:** Manual muscle test.	1. All subjects showed improvement in one or more of their manual muscle scores with the most dramatic occurring in the tricep muscle group (average increase 1.1±0.2 for L triceps, 0.7±0.1 for R). 2. Results show NMS in combination with resistive exercise can be used safely and assists in the strengthening of voluntary contractions.

Discussion

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.
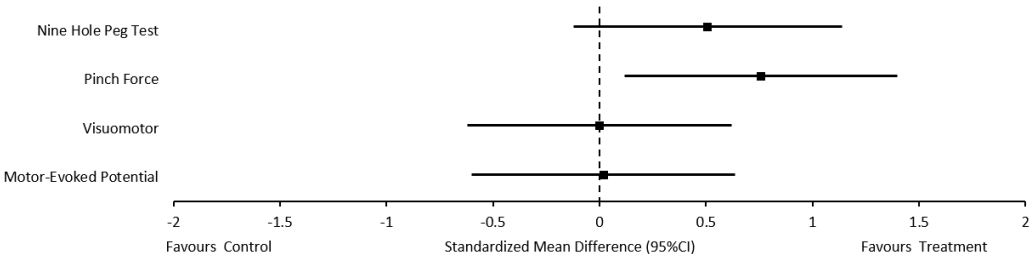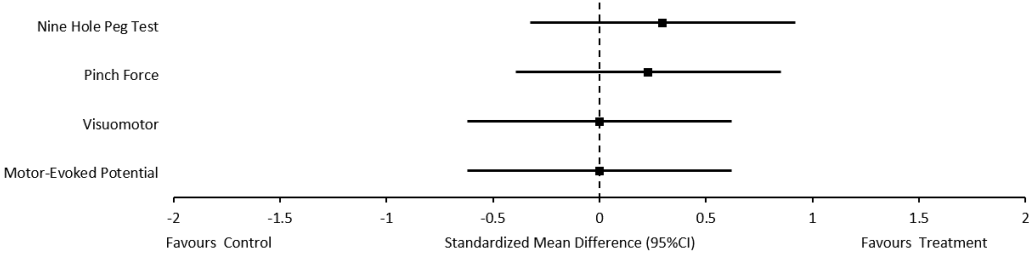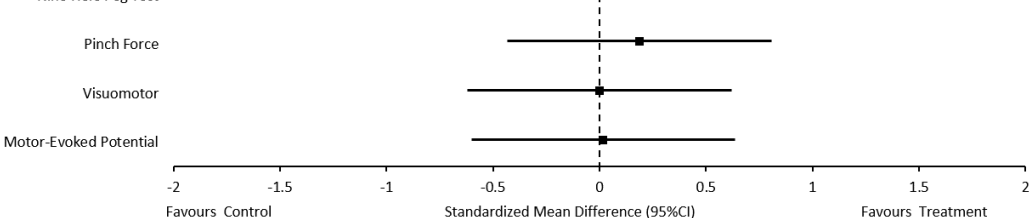
5.2 Transcutaneous Electrical Nerve Stimulation

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

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
Gomes-Osman & Field-Fote 2015 USA Crossover RCT	**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.	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).

| N=24 | **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. | 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.

Gomes-Osman & Field-Fote et al. 2015; TENS vs. VIB

Gomes-Osman & Field-Fote et al. 2015; TENS vs. tDCS

Gomes-Osman & Field-Fote et al. 2015; VIB vs. tDCS

| | **Population:** *Experimental Group (n=11):* Mean Age: N/R; Gender: males=7, females=4; | 1. A significant Time x Group interaction was reported for JTHF scores with the |

Hoffman & Field-Fote 2013 USA RCT PEDro=4 N=24	Level of Injury: C3=2, C4=3, C5=1, C6=3, C7=2; Severity of Injury: AIS B=1, AIS C=4, AIS D=6. *Control Group (n=13):* Mean Age: N/R; Gender: males=10, females=3; Level of Injury: C4=2, C5=2, C6=5, C7=4; Severity of Injury: AIS A=2, AIS B=3, AIS C=5, AIS D=3. **Intervention:** Patients were randomly assigned to either an experimental group or a control group then further divided into four conditions, Unimanual Somatosensory Stimulation (Uni-SS), Bimanual SS (Bi-SS), Unimanual Functional Electrical Stimulation (Uni-FES) and Bimanual FES (Bi-FES). For patients who received SS, electrodes were placed over median nerve in the wrist. FES electrodes were also placed on the median nerve in the wrist but FES was only triggered when muscle activation exceeded the threshold value. During each session, patients completed a set of activities (either unimanually or bimanually) including grasping, grasping and rotation, pinching, pinch with rotation, and finger isolation. Control patients received the interventions after an initial delayed control period. The interventions were provided 2hr/day, 5day/wk for a total of 3 wk. Assessments were conducted at baseline and at post treatment. **Outcome Measures:** Jebsen Taylor Hand Function Test (JTHF), Corticomotor activity, Chedoke Arm and Hand Activity Inventory (CAHAI).	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.

Hoffmann et al. 2013; FES+SS vs. Delayed Intervention (Control)

JTHFT	0.34 (-0.47,1.15)
CAHAI	0.22 (-0.59,1.02)
Pinch	0.07 (-0.73,0.88)
SWMT	0.00 (-0.80,0.80)
HAQ	0.08 (-0.72,0.88)

Favours Control — Standardized Mean Difference (95%C.I.) — Favours Treatment

Hoffmann et al. 2013; Bimanual vs. Unimanual

JTHFT	0.08 (-0.72,0.89)
CAHAI	0.33 (-0.48,1.14)
Pinch	0.03 (-0.77,0.84)
SWMT	0.30 (-0.51,1.11)
HAQ	0.01 (-0.79,0.81)

Favours Control — Standardized Mean Difference (95%C.I.) — Favours Treatment

	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).

Beekhuizen & Field-Fote 2008 USA RCT PEDro=5 N_Initial=24; N_Final=18 placed in left cell of above row.

| Beekhuizen & Field-Fote 2005 USA RCT PEDro=8 N=10 | **Population:** Age: 22-63 yr; Gender: males=9, females=1; Level of injury: C5-C7; Severity of injury: AIS C=4, D=6; Time since injury: 12-154 mo.
Intervention: 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.
Outcome Measures: Maximal pinch grip force, Wolf motor function test timed task scores, Jebson hand function test scores, Stimulus intensity required to elicit motor threshold response in muscles, Motor evoked potentials amplitude. | 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. |

Forest plot: Hoffmann et al. 2013; FES vs. SS. Standardized Mean Difference (95%C.I.). Favours Control / Favours Treatment. JTHFT 0.12 (-0.69,0.92); CAHAI 0.04 (-0.76,0.85); Pinch 0.05 (-0.75,0.86); SWMT 0.13 (-0.68,0.93); HAQ 0.11 (-0.70,0.91).

Gomes-Osman et al., 2017 USA RCT PEDro=6 N=37	**Population:** *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: AISA 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: AISA 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: AISA A=0, B=0, C=9, D=1. **Intervention:** 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. **Outcome Measures**: Grip force (precision and power); Tactile sensation.	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).
Gad et al., 2018 USA Pre-Post N=6	**Population:** Mean age=40.2 yr; Gender: males=5, females=1; Time since injury: 10 yr; Level of injury: C4 - C8; Severity of injury: AISA A=0, B=2, C=4, D=0. **Intervention:** 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. **Outcome Measures**: Voluntary hand function (handgrip force).	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).
Nasser et al., 2014 Eqypt Pre-Post N=25	**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

Adopted from: https://i.pinimg.com/originals/8c/bb/41/8cbb419d16dbf770ea9ee8872e2d3f3d.jpg

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). These 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

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
Harvey et al., 2017 Australia RCT PEDro=7 N=70	**Population:** *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: AISA 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: AISA A=10, B=5, C=9, D=9. **Intervention:** 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	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>0.05).

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
	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. **Outcome Measures**: Hand and arm function (Modified Action Research Arm Test).	
Popovic et al., 2006 Canada RCT PEDro=6 N=21	**Population:** Age: 25-70 yr; Level of injury: tetraplegia; Severity of injury: AIS A-D, incomplete; Time Since Injury: 15-243 day; Chronicity: acute/subacute. **Intervention:** The control group received conventional Occupational Therapy; Intervention group received Functional Electrical Therapy and conventional Occupational Therapy. **Outcome Measures:** Functional Independence Measure (FIM), Spinal Cord Independence Measure (SCIM), Rehabilitation Engineering Laboratory Hand Function Test (REL Test), Consumer Perceptions.	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.
Iwahashi et al., 2017 Japan RCT PEDro=5 N=29	**Population:** *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 **Intervention:** Participants were randomized to either a therapeutic electrical stimulation (n=15) or control group (n=14). The therapeutic 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. **Outcome Measures:** Total passive motion of the fingers; Edema; Upper Extremity Motor Score of the International Standards for the Neurological Classification of Spinal Cord Injury (UEMS).	1. There were no significant differences between any of the groups at three mo for all outcome measures ($p>0.05$).
Zoghi & Galea 2017 Australia RCT PEDro=3 N=7	**Population:** *Intervention (n=3):* Gender: males=3; Level of injury: C3 – C8; Severity of injury: AISA A=1, B=0, C=0, D=2. *Control (n=4):* Gender: males=3, females=1; Level of injury: C3 – C8; Severity of injury: AISA A=0, B=1, C=1, D=2. **Intervention:** Participants were randomized to a control group receiving the standard of care	1. Some participants showed significant improvement after 8 wk of rehabilitation based on ARAT and GRASSP scores ($p<0.05$). This improvement was not reflected in the pattern of muscle activation that was captured by BMCA.

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
	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.	
Hoffman & Field-Fote 2013 USA RCT PEDro=4 N=24	**Population:** *Experimental Group (n=11):* Mean Age: N/R; Gender: males=7, females=4; Level of Injury: C3=2, C4=3, C5=1, C6=3, C7=2; Severity of Injury: AIS B=1, AIS C=4, AIS D=6. *Control Group (n=13):* Mean Age: N/R; Gender: males=10, females=3; Level of Injury: C4=2, C5=2, C6=5, C7=4; Severity of Injury: AIS A=2, AIS B=3, AIS C=5, AIS D=3. **Intervention:** Patients were randomly assigned to either an experimental group or a control group then further divided into four conditions, Unimanual Somatosensory Stimulation (Uni-SS), Bimanual SS (Bi-SS), Unimanual Functional Electrical Stimulation (Uni-FES) and Bimanual FES (Bi-FES). For patients who received SS, electrodes were placed over median nerve in the wrist. FES electrodes were also placed on the median nerve in the wrist but FES was only triggered when muscle activation exceeded the threshold value. During each session, patients completed a set of activities (either unimanually or bimanually) including grasping, grasping and rotation, pinching, pinch with rotation, and finger isolation. Control patients received the interventions after an initial delayed control period. The interventions were provided 2hr/day, 5day/wk for a total of 3 wk. Assessments were conducted at baseline and at post treatment. **Outcome Measures:** Jebsen Taylor Hand Function Test (JTHF), Corticomotor activity, Chedoke Arm and Hand Activity Inventory (CAHAI).	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 pre- and post-intervention data.	

Author Year Country Research Design Score Total Sample Size	Methods	Outcome

Hoffmann et al. 2013; FES+SS vs. Delayed Intervention (Control)

JTHFT	0.34 (-0.47,1.15)
CAHAI	0.22 (-0.59,1.02)
Pinch	0.07 (-0.73,0.88)
SWMT	0.00 (-0.80,0.80)
HAQ	0.08 (-0.72,0.88)

-2   -1.5   -1   -0.5   0   0.5   1   1.5   2
Favours Control   Standardized Mean Difference (95%C.I.)   Favours Treatment

Hoffmann et al. 2013; Bimanual vs. Unimanual

JTHFT	0.08 (-0.72,0.89)
CAHAI	0.33 (-0.48,1.14)
Pinch	0.03 (-0.77,0.84)
SWMT	0.30 (-0.51,1.11)
HAQ	0.01 (-0.79,0.81)

-2   -1.5   -1   -0.5   0   0.5   1   1.5   2
Favours Control   Standardized Mean Difference (95%C.I.)   Favours Treatment

Hoffmann et al. 2013; FES vs. SS

JTHFT	0.12 (-0.69,0.92)
CAHAI	0.04 (-0.76,0.85)
Pinch	0.05 (-0.75,0.86)
SWMT	0.13 (-0.68,0.93)
HAQ	0.11 (-0.70,0.91)

-2   -1.5   -1   -0.5   0   0.5   1   1.5   2
Favours Control   Standardized Mean Difference (95%C.I.)   Favours Treatment

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
Hodkin et al., 2018 U.K. PCT N=6	**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.	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.

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
	Outcome Measures: Action Research Arm Test (ARAT); Qualitative feedback.	

Table 14.1 Functional Electrical Stimulation Systematic Reviews

	Methods	Outcome
Patil et al., 2015 UK Review of published articles between September 2009-September 2014 N= 5	**Method:** 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. **Databases:** EMBASE, PsycInfo, PubMed and Food, Science and Technology abstracts. **Level of evidence:** Jovell and Navarro-Rubio classification: *Good (I-II):* Meta-analysis of randomized controlled trials (RCTs), Large-sample RCTs; *Good-to-fair (III-V):* Small-sample RCTS, non-randomized controlled prospective trials, non-randomized controlled retrospective trials; *Fair (VI-VII):* cohort studies, case-control studies; *Poor (VIII-IX)*: non-controlled clinical series; descriptive studies, anecdotes or case reports. **Questions/measures/hypothesis:** Examine the evidence for FES on motor control and functional ability of the upper limb in spinal cord injured people.	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.

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 determing effective electrical stimulation patterns. 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
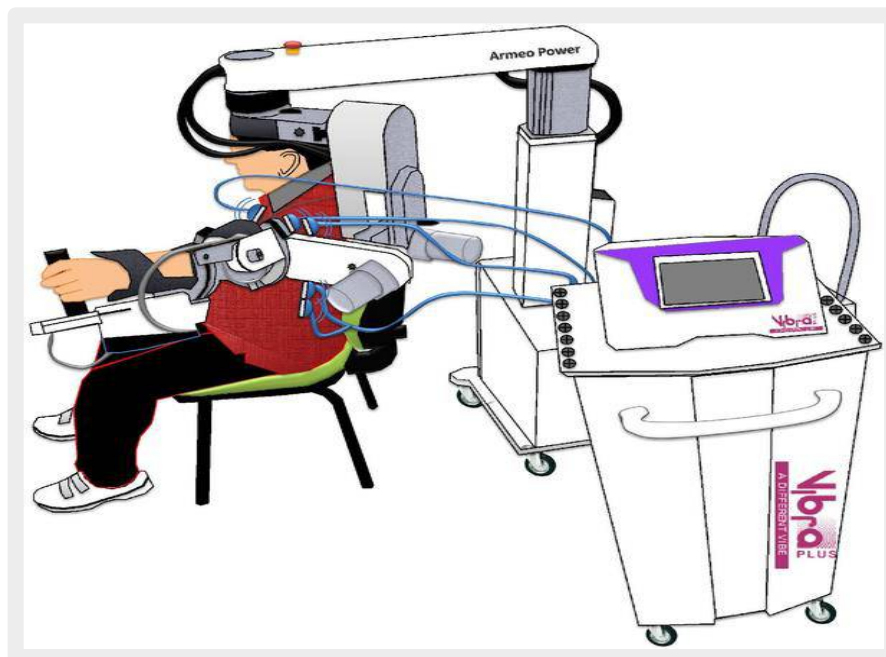
To date, many rehabilitative therapies have been proposed to help with muscle function and spasticity, such as, passive standing, muscle strengthening and electrical stimulation (Ji et al., 2016). Recently, interest has focused on muscle vibration, which aims to prevent/treat muscle atrophy and spasticity 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

Author Year Country Research Design Score Total Sample Size	wMethods	Outcome
Gomes-Osman & Field-Fote 2015 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	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.

	(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.	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.

Gomes-Osman & Field-Fote et al. 2015; TENS vs. VIB

Gomes-Osman & Field-Fote et al. 2015; TENS vs. tDCS

Gomes-Osman & Field-Fote et al. 2015; VIB vs. tDCS

Backus et al. 2014 USA Pre-Post N=18	**Population:** Mean age: 40.5±13.0 yr; Gender: males=8, females=2; Level of injury: C2-C3=3, C4-C7=7; Mean ASIA motor score: 15.8±3.9; Mean time since injury: 3.0±1.1 yr.	1. No significant change in MAS scores (p=0.371) or ISNCSCI scores (p=0.299 for motor, p=0.459 for sensory-light tough, p=0.343 for sensory-pin prick).

Intervention: Test effect of assisted movement with enhanced sensation (AMES) using vibration to antagonist muscle to reduce impairments and restore upper limb function in people with incomplete tetraplegia. Two or three sessions over 9-13 wk per participant. **Outcome Measures:** Strength and active motion tests on the AMES device, International Standards for the Neurological Classification of SCI (ISNCSCI) motor and sensory examinations, Modified Ashworth Scale (MAS), grasp and release test (GRT), Van Lieshout Test (VLT), Capabilities of Upper Extremity questionnaire (CUE).	2. Strength test scores increased significantly for MCP extension (p≤0.01) and flexion (p≤0.05) and for wrist extension (p≤0.001) and flexion (p≤0.01). 3. Active motion test scores increased significantly for MCP joints (p≤0.001) and wrist (p≤0.001). 4. Out of GRT, VLT and CUE scores, only GRT scores were significantly improved after training and slightly between 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 15) 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
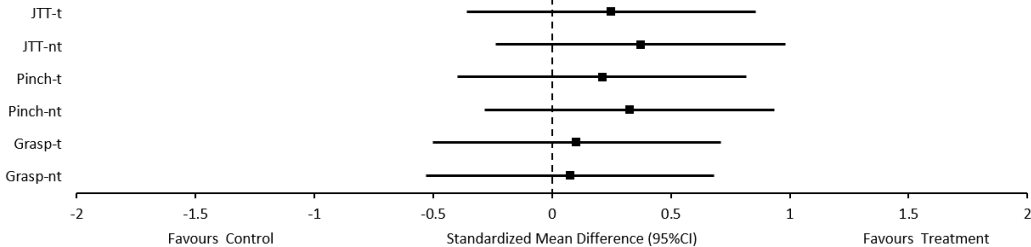
Transcranial magnetic stimulation (TMS) is a non-invasive and painless method of stimulating neural activity within the corticospinal system (Tazoe and Perez, 2015). A coil is placed on the scalp over an area of interest (e.g. motor cortex) to generate an electromagnetic field, which alters electrical 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 Interventions

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
Tolmacheva et al. 2017 Finland RCT PEDro=9 N=5	**Population:** Mean age=48 yr; Gender: males=4, females=1; Time since injury: 3.8 yr; Level of injury: C3 – C7; Severity of injury: AISA 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.	1. One month after the last stimulation session, a significant improvement was observed in the TMS/PNS group (p<0.0001). 2. The improvement was significantly higher in TMS/PNS than PNS treated hands (p=0.046).

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

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

Gomes-Osman & Field-Fote et al. 2014; rTMS+RTP vs. Sham

Bunday et al. 2018 USA PCT N=31	**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: AISA 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	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.

	(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).	
Bunday et al. 2014 USA Prospective Controlled Trial N=43	**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 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).	1. Significant effect of group (p=0.001) but not task (p=0.21) or interaction (p=0.19) on FDI mean rectified EMG activity. 2. EMG activity increased in SCI patients taking baclofen (SCIBac) (p=0.001) and patients who never took baclofen (SCINo-Bac) (p=0.01) compared with controls; no significance between patient groups (p=0.95). 3. Both SCI and control groups maintained similar EMG activity in the FDI muscle during precision grip and index finger abduction (p=0.21). 4. During index finger abduction, controls (p=0.01), SCIBac (p<0.001) and SCINo-Bac (p=0.04) more EMG activity in FDI compared to APB at all Transcranial magnetic stimulation (TMS) intensities. 5. Significant decrease in MEP size in controls (p<0.001) and SCIBac (p=0.001) during precision grip compared with index finger abduction. 6. At increasing stimulus intensities, MEP sizes in control subjects were significantly larger than SCINo-Bac and SCIBac (p<0.001). 7. FDI cervicomedullary MEPs decreased during precision grip compared with index finger abduction in controls (p<0.01) and SCIBac (p<0.01) but not SCINo-Bac (p=0.57). 8. No effect of task, group or their interaction on F-wave amplitude or F-wave persistence (p>0.05). 9. Significant effect of task (p<0.001), but not group (p=0.39) or their interaction (p=0.20) on svEMG. 10. Significant decrease in svEMG area during precision grip compared with index finger abduction in controls (p=0.03), SCIBac (p=0.02) and SCINo-Bac (p=0.02).
Peterson et al. 2017 USA PCT N=17	**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	1. MEP amplitude was significantly greater in the transferred biceps relative to non impaired biceps in overhead reach regardless of forearm orientation (p<0.001). 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.

	(TMS) was delivered to the motor cortex with the arm in functional postures at rest in intervention and control groups. **Outcome Measures**: Motor-evoked potential (MEP); Elbow extension.	
Belci et al., 2004 UK Pre-post N=4	**Population:** Age: 41-54 yr; Gender: males=3, females=1; Level of injury: C5=4; Severity of injury: AIS D=4; Time since injury: 1.25-8 yr. **Intervention:** Five days of sham repetitive transcranial magnetic stimulation (rTMS) followed by five days of therapeutic stimulation (rTMS). **Outcome Measures:** ASIA Impairment Scale (AIS), Nine Hole Peg Board.	1. No difference between patients when looking at the assessments done after baseline and after sham intervention. 2. The level of intracortical inhibition was reduced to 37.5±8.0% of pre-treatment levels during the week of therapeutic treatment (p<0.05) and returned to 90.2±15% of pre-treatment levels during the follow-up period. 3. This was linked to improvements in clinical measures of both motor and pinprick of 4-10% during treatment week. (p<0.05). 4. 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

Adopted from: https://sharpbrains.com/wp-content/uploads/2018/10/tdcs.jpg
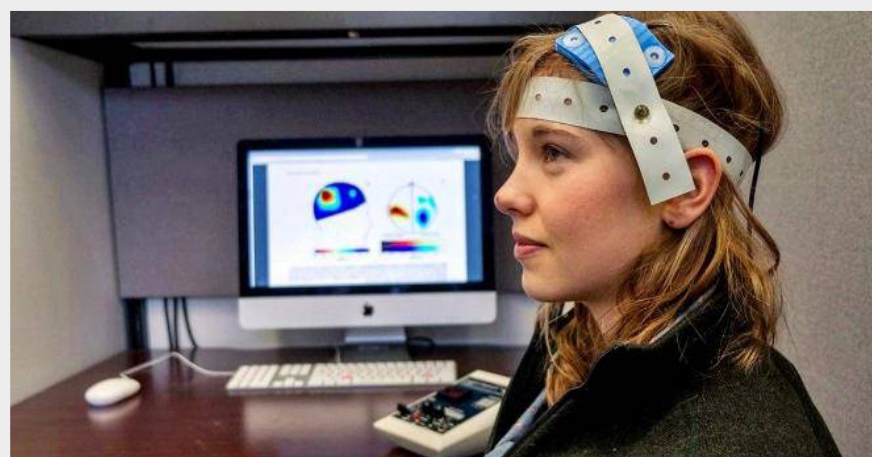
Transcranial direct current stimulation (tDCS) is a method of non-invasive brain stimulation that involves the application of low intensity electrical current (1-2 mA) to the head, via surface electrodes placed on the scalp in an area of cortical interest (James et al., 2018). In contrast to transcutaneous 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

Author Year Country Research Design Score Total Sample Size	Methods	Outcomes
Cortes et al., 2017 USA RCT – Crossover PEDro=7 N=11	**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: AISA A=0, B=5, C=5, D=1. **Intervention:** Participants were randomized to receive 20 minutes of 1mA, 2mA, or sham anodal transcranial direct current stimulation (tDCS) stimulation over the targeted motor	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>0.05).

	cortex for three separated sessions. Outcome measures were assessed before and after each session. **Outcome Measures**: Hand motor performance kinematics (grasp mean to peak speed ratio); Box and Blocks test (BB).	
Potter-Baker et al., 2018 USA Cohort N=8	**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: AISA 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: AISA A=0, B=1, C=0, D=3. **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).	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 three mo after the intervention compared to controls. 2. Five out of six participants demonstrated improvements in their UEMS post-test. 3. No significant differences were observed in functional tasks at post-test and follow-up (ARAT and NHPT) (p>0.05).

Discussion

Numerous studies have investigated the effects 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 proximial/hand muscles, however, larger clinical trials are necessary.

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.

7.0 Pharmacological Interventions

7.1 Baclofen

Adopted from: https://mmcneuro.files.wordpress.com/2013/02/itb.jpeg
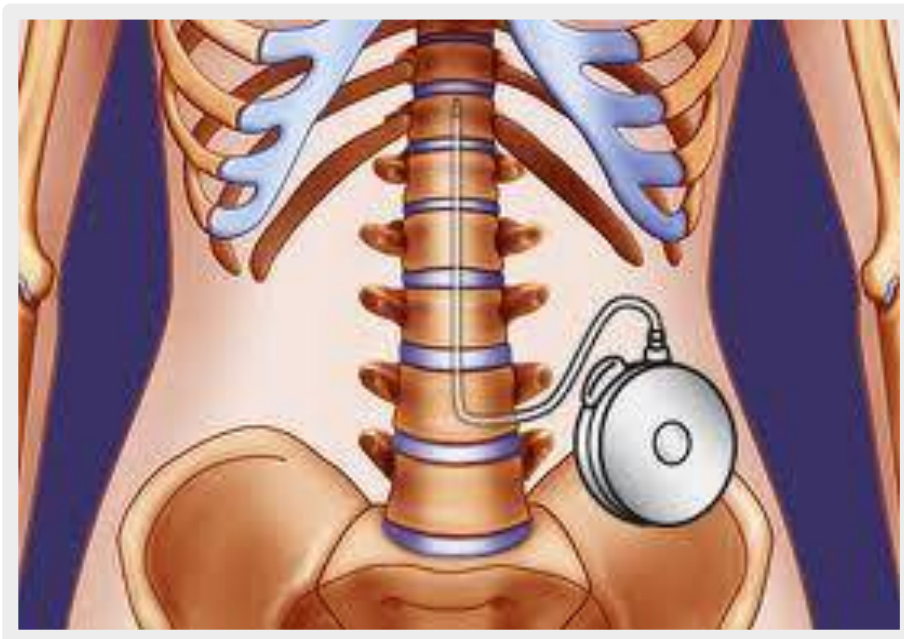
Cervical injuries of the spinal cord frequently lead to hypertonia characterized by disabling spasticity and dystonia involving the upper and lower limb. Spasticity has been defined by Lance

(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

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
Burns & Meythaler 2001 USA Case Series N=14	**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.	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<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<0.0001 Friedman). 5. Dosage requirements increased during the 12-mo follow-up period, statistically significant (p<0.0001, Friedman). 6. Statistically significant declines in upper extremity spasm scores (1.8 points, p=0.012), reflex scores (1.4 points, p<0.0001) and Ashworth

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
		scores (0.6 points, p<0.0001) for the 1-yr follow-up period.
Bunday et al. 2014 USA Prospective Controlled Trial N=43	**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 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).	1. Significant effect of group (p=0.001) but not task (p=0.21) or interaction (p=0.19) on FDI mean rectified EMG activity. 2. EMG activity increased in SCI patients taking baclofen (SCIBac) (p=0.001) and patients who never took baclofen (SCINo-Bac) (p=0.01) compared with controls; no significance between patient groups (p=0.95). 3. Both SCI and control groups maintained similar EMG activity in the FDI muscle during precision grip and index finger abduction (p=0.21). 4. During index finger abduction, controls (p=0.01), SCIBac (p<0.001) and SCINo-Bac (p=0.04) more EMG activity in FDI compared to APB at all Transcranial magnetic stimulation (TMS) intensities. 5. Significant decrease in MEP size in controls (p<0.001) and SCIBac (p=0.001) during precision grip compared with index finger abduction. 6. At increasing stimulus intensities, MEP sizes in control subjects were significantly larger than SCINo-Bac and SCIBac (p<0.001). 7. FDI cervicomedullary MEPs decreased during precision grip compared with index finger abduction in controls (p<0.01) and SCIBac (p<0.01) but not SCINo-Bac (p=0.57). 8. No effect of task, group or their interaction on F-wave amplitude or F-wave persistence (p>0.05). 9. Significant effect of task (p<0.001), but not group (p=0.39) or their interaction (p=0.20) on svEMG. 10. Significant decrease in svEMG area during precision grip compared with index finger abduction in controls (p=0.03), SCIBac (p=0.02) and SCINo-Bac (p=0.02).

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 little or no upper limb function (Freehafer et al., 1984; Kirshblum & Lin 2018). Despite the potential benefits, the option to receive reconstructive surgery in persons with SCI is often declined. This decision is influenced by a temporal element, including hope for a cure or recovery from SCI (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 (Sinnot 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 even sexual function among persons with tetraplegia. In a survey of tetraplegia patients, 75% responded that hand function was very important for their independence in 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 and 44% of the surveyed individuals reported an interest in receiving upper extremity reconstructive surgery (Wagner et al., 2007). More recently, Rivers and colleagues (2018) conduced 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 units. T 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 centres 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; Guttmann 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 to the function of their arm and hands. Despite underutilization of surgery, however, 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 are followed by a rehabilitation team that includes an orthopedic surgeon, rehabilitation physiatrist, and therapist over a significant period of time. The identified criteria for selection are as follows: at least one-year post-injury, completed a comprehensive rehabilitation program, neurologically stable, and psychologically adjusted to their injury.

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 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

The most commonly performed surgeries for reconstructive pinch are:
1. Key-Pinch Grip
   - Brachioradialis to Extensor Carpi Radialis Longus (ECRL), Flexor Pollicis Longus (FPL) split tenodesis.
   - The IP joint of the thumb may need to be stabilized to prevent excessive IP flexion.

2. Key-Pinch Grip with or without Hook Grip
   - Brachioradialis (BR) to FPL with or without Flexor Digitorum Profundus (FDP) tenodesis or BR to ECRL.

3. Key-Pinch Grip and Hook Grip
   - BR or Pronator Teres (PT) to FPL and BR or ECRL to FDP.

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

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

Table 19 Pinch Interventions post-SCI

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
Wangdell et al., 2018 Sweden Cohort N=37	**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; Level of injury: C5 – C7; Severity of injury: not reported. **Intervention:** Participants with (n=17) and without (n=20) preoperative neuropathic pain in the arm/hand were evaluated for outcome measures pre and post surgical grip reconstruction. **Outcome Measures**: Grip strength; Grasp ability; Prioritized activity outcome.	1. There were no significant differences between the pain and no pain groups regarding grip strength, grip ability or activity performance and satisfaction (p>0.05). 2. Both groups experienced improvements in all aspects of the prioritized activity outcome and there were no differences in the ability to fulfill postoperative treatment (p>0.05).
McCarthy et al., 1997 USA Pre-Post N=135	**Population:** Age: 8-58 yr; Gender: males=103, females=30; Level of injury: tetraplegia; Follow-up time: 3-24 mo. **Intervention:** Extrinsic hand reconstruction with intrinsic balancing procedures versus extrinsic reconstructions without intrinsic balancing procedures. **Outcome Measures:** Pre-and post-operative assessments of grip strength (on the second position of the Jamar dynamometer), Activities of Daily Living (ADL).	1. All patients had preoperative grip strength of zero. At an average follow-up period of 31 mo, the average final grip strength was 69N (7kg) and the ADL improvement score averaged 35.5. 2. Patients who underwent an intrinsic procedure had a statistically stronger grip (72N) than patients who did not undergo an intrinsic procedure (p=0.026). 3. Ocular group: Five patients with an intrinsic procedure had a statistically stronger grip than patients without an intrinsic procedure (p=0.028). 4. With the exception of Ocular group 7, in which eight patients did not undergo an intrinsic procedure due to their ability to balance tension between the extensors and flexors, all other Ocular groups with an intrinsic reconstruction showed stronger grip than patients without an intrinsic reconstruction. 5. ADL improvements scores were higher but not statistically significant for those with intrinsic rebalancing versus those without rebalancing. 6. There was significant difference between the hands treated by FDS lasso and those treated by intrinsic tenodesis when patients were stratified by Ocular level.

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
		7. There was also no significant difference in grip strength results between the FDS lasso versus the intrinsic tenodesis procedures when stratified by both Ocular level and type of extrinsic reconstruction, both surgical techniques were effective in improving strength and ADL.
House et al., 1992 USA Case Series N=18	**Population:** Age: 16-29 yr; Gender: males=14, females=4; Level of injury: C5-C6; Time since injury: 16 mo-13 yr; Mean follow-up time: 3.5 yr. **Intervention:** Carpal-metacarpal fusion was performed; along with extensor pollicis longus tenodesis and motor transfer to flexor pollicis longus. **Outcome measures:** Function of the hand, subjective pain scale, Level of satisfaction with surgery and rehabilitation, Activities of Daily Living (ADL).	1. All patients reported a significant increase in independent hand function in relation to ADLs, no patient reported hand function was worse after surgery. 2. Technique provided a reliable and reproducible key pinch. 3. All patients had significant improvement in functional ADLs and highly satisfied with results of surgery.
Waters et al., 1985 USA Case Series N=15	**Population:** Age: 20-47 yr; Gender: males=13, females=2; Time since injury: 8 mo-18 yr; Follow-up time: 8-48 mo. **Intervention:** Surgery. **Outcome Measures:** Pinch strength, Activities of Daily Living (ADL) reports, Brachioradialis (BR), Flexor Pollicis Longus (FPL), Flexor Digitorum Profundus (FDP), Extensor Capri Radialis Longus (ECRL), Extensor Pollicis Brevis (EPB).	1. Release of the BR and suture to the FPL. In 16/17 hands, fixation of the IP joint of the thumb was obtained with a Moberg screw. 11/17 patients lacked active thumb extension had tenodesis of the thumb extensors to the MCP to prevent excessive flexion of the MCP joint. 2. FPL and EPB were secured to the dorsum of the MC. 6/11 patients did not require tenodesis had sufficient strength in the FPL to extend the thumb. 3. Two of six EIP was transferred to FPL for active extension. 4. Satisfactory finger flexion present in 10 hands. In seven hands: intertendinous suture of all FDP tendons in four patients who had active flexion in the ulnar profundi of small and ring finger, but could not flex index finger. 5. Transfer of PT to all FDP tendons in two patients; transfer of ECRL to all FDP tendons in one patient; transfer of FCU to all FDP tendons in one patient. 6. Preoperative lateral pinch ranged from 0-0.15 lbs, post-operative lateral pinch ranged from 2.2-4 (depending on elbow and wrist position). 7. Residual motor function in triceps (fair plus) (11 patients) and pinch strength; lateral pinch 5.1 lbs,

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
		strength fair or less (6 patients) 2.0 lbs pinch.
		8. 87% (13/15) reported significant improvement; four patients wanted stronger pinch.
		9. 80% (12/15) could name four ADL activities that they were able to perform.
		10. 13% (2/15) were dissatisfied.
		11. 20% (3/15) reported discomfort tip of thumb.

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 over all ability to complete daily living tasks.

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

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-pinch 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-pinch 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

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
Coulet et al., 2018 France PCT N=31	**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. **Intervention:** Participants received active (n=18) or passive (n=22) key pinch reconstructive surgery using a technique that either preserved the carpometacarpal (CMC) joint or required arthrodesis. Outcome measures were assessed at baseline and an average of 7.3 yr following surgery. **Outcome Measures**: Grip strength; Key pinch opening; Stability.	1. Active key pinch strength was significantly higher than passive key pinch strength (p<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>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>0.05). 4. No significant differences in key pinch stability were observed for either surgical technique (p>0.05).
Mohindra et al., 2017 India Pre-Post N=12	**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. **Intervention:** Key pinch was restored using Brachioradialis to Flexor Pollicis Longus transfer and hook using Pronator Teres to Flexor Digitorum Profundus transfer. Outcome measures were	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

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
	assessed at baseline, six mo and a final follow up time averaging 26 mo post surgery. **Outcome Measures**: Key pinch and hook grip (Modified Lamb and Chan score).	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.
Forner-Cordero et al., 2003 Spain Retrospective Follow-up N$_{Initial}$=15; N$_{Final}$=14	**Population:** Age: 20-62 yr; Level of injury: C4-C7; Time since injury: 15-239 mo. **Intervention:** Surgical reconstruction. **Outcome Measures:** Increased hand movement and strength, Activities of Daily Living (ADL), Patient's satisfaction, Fulfillment of patient's expectations, Surgical complications.	1. Strength: key-pinch strength average of 17.2 kPa (5-50 kPa); grasp strength average 18.8 kPa (3-45 kPa). 2. No relation found between the ADL test and the key pinch strength (p=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.
Meiners et al., 2002 Germany Case Series N$_{Initial}$=24; N$_{Final}$=22	**Population:** Age: 21-57 yr; Gender: males=21, females=3; Time since injury: 9-59 mo. **Methodology:** Surgery. **Outcome Measures:** Activities of Daily Living (ADL) questionnaire, Satisfaction Survey, Key grip, Lateral force grip.	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.
Lo et al., 1998 Canada Case Series N=9	**Population:** Level of injury: C5-6; Time since injury: ≥1 yr. **Intervention:** Surgery. **Outcome Measures:** Key pinch strength; Minnesota rate of manipulation; Satisfaction with surgery.	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.
Failla et al., 1990 USA Case Series N=8	**Population:** Age: 9-58 yr; Level of injury: tetraplegia. **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.
Gansel et al., 1990 USA Case Series N=19	**Population:** Age: 20-47 yr. **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.

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
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 in 17% of the extremities in group III, 71% in group IV, and 33% in group V.
Colyer & Kappelman 1981 USA Case Series N=8	**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.
Wangdell et al., 2014 Sweden Observational N=11	**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

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
		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. 6. After phase 3, a theme emerged of higher independence with patients stating several examples of autonomy.
Wangdell et al., 2013 Sweden Observational N=11	**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.	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

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
		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 retrospectrive 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). 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).

8.2.1 Posterior Deltoid to Triceps

Posterior deltoid-to-triceps transfer is the most commonly performed surgery for elbow extension. The methodological details and results of seven deltoid-to-triceps transfer studies are outlined in Table 21.

Table 21 Reconstructive Surgery: Elbow Extension (Deltoid to Triceps)

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
Rabischong et al., 1993 France Prospective Controlled Trial N=20	**Population:** Mean age: 33.6 yr; Level of injury: C6; Time since injury: 28-173 mo. **Intervention:** The arm and forearm were locked in position and a force transducer was used to assess the torque output isometrically. The muscle was tested at 6 different lengths with the shoulder abducted at 90^0. **Outcome Measures:** Maximal torque.	1. The muscle was tested at six different lengths (130^0, 110^0, 90^0, 70^0, 45^0 and 0^0 of elbow flexion) with the shoulder abducted at 90. 2. When compared, the absolute values (dimension of torque) were significantly different between groups ($0.00001 < p < 0.002$). 3. The expression of this relation (% of maximum values) revealed significant statistical differences ($p < 0.002$) at 90^0 and 70^0 degree of elbow flexion; peak torque was at 130^0 in experimental group and 110^0 in control group with a plateau between 110^0 and 70^0. 4. Length-tension relationship was fairly similar among control group, but great differences in experimental group.
Dunkerley et al., 2000 UK Case-Control $N_{Initial}=15$; $N_{Final}=11$	**Population:** Age: 23-38 yr; Time since injury: 5-16 yr. **Intervention:** Surgery.	1. Both groups scored identically on the FIM. 2. No significant differences in mobility were noted ($p=0.256$, and $p=0.432$).

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
	Outcome Measures: Questionnaire, Functional independence measure (FIM), 10m push, Figure of 8 push.	3. Questionnaire was answered only by the treatment group; clients gave positive response to the questions.
Remy-Neris et al., 2003 France Pre-Post N=16	**Population:** Mean age: 27 yr; Gender: males=11, females=5. **Intervention:** Surgery. Control group members sat on a chair, while those with tetraplegia sat in a wheelchair. All were asked to perform two movements; a straight arm lateral and maximal raising and return. **Outcome Measures:** Straight Arm Raising, Hand-to-nape-of-neck movement.	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 ($p<0.0001$). 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.
Dunn et al., 2017 New Zealand Case Series N=75	**Population:** Mean age=31 yr; Gender: males=68, females=7; Time since injury: 23±9 yr; Level of injury: C4-C6; Severity of injury: AISA A/B=63, C/D=5, unknown=7. **Intervention:** No intervention. A retrospective chart review of deltoid-triceps transfers in patients with tetraplegia was performed between 1983 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.	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 autologous tendon grafting (tibialis anterior and hamstring grafts) when compared to the synthetic graft group ($p<0.05$). 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 USA Case Series N=10	**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 USA Case Series N_{Initial}=22; N_{Final}=18	**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.

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
		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.

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 tricep 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 at least 5/5 elbow flexion of the MRC scale, active brachialis, 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 usually requires two stages and two transfers. However, it is only indicated in patients with fixed elbow flexion contractures greater than 45 degrees.

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)

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
Mulcahey et al., 2003 USA RCT PEDro=6 N=9	**Population:** Gender: males=7, females=2; Level of injury: tetraplegic; ICSHT: 0-4; Tendon transfer for elbow extension: deltoids n=8, biceps n=8. **Intervention:** Surgery. **Outcome Measures:** Muscle strength, Flexion torque, Modified University of Minnesota Tendon Transfer Functional Improvement Questionnaire, Canadian Occupational Performance Measure (COPM), Activities of Daily Living (ADL).	1. After surgery, elbow extension muscle strength was improved in bicep and deltoid groups (p<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 deltoid transfers completed. 4. No significant difference between the groups was found for elbow flexion torque (47% reduction in torque after two yr versus baseline).

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
		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.
Medina et al., 2017 Spain Pre-Post N=4	**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. **Intervention:** 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. **Outcome Measures**: Elbow extension; Muscle strength assessment scale (MRC); Disabilities of the Arm, Shoulder and Hand (DASH) questionnaire.	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>0.05).
Kozin et al., 2010 USA Case Series $N_{Initial}$=45; N_{Final}=40	**Population:** Mean age: 17.3 yr; Level of injury: C5=10, C6=29, C7=1. **Intervention:** Surgery for a biceps to triceps tendon transfer (36 left, 32 right). **Outcome Measures:** Manual muscle testing, Canadian Occupational Performance Measure (COPM).	1. Manual muscle testing for elbow extension revealed a statistically significant increase in preoperative to postoperative muscle strength (p<0.001). 2. 42/68 arms able to extend completely against gravity (manual muscle testing 3/5 or greater). 3. 9/68 arms had mild extension lag against gravity (manual muscle testing of 3/5). 4. 75% (51/68) arms were able to function overhead. 5. 17/68 arms were less than 3/5 (lack of strength attributed to a post-operative complication). 6. Improvement in one goal on the COPM was observed by each patient. 7. COPM total mean score statistically increased from 2.6 to 5.6 and from 1.8 to 5.7 for performance (p<0.001) and satisfaction (p<0.001), respectively.
Kuz et al., 1999 USA Case Series N=3	**Population:** Level of injury: tetraplegia. **Intervention:** Surgery. **Outcome Measures:** Self-reported satisfaction and need for adaptive aids.	1. No statistical results reported. 2. Subjects indicated they were satisfied with the surgery. 3. Activities that required precision hand placement had improved.

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
		4. Elimination of the need for some adaptive aids was possible post-surgery.

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 muscle strength as well as performance and satisfaction. However, they did not report a significant improvement in 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

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
Dunn et al., 2014 New Zealand Cohort N=19	**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 & Chan questionnaire (LCQ), Key pinch strength, Grip strength, Type of wheelchair used.	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<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.
Friden et al., 2012b Sweden Case Control N=12	**Population:** *Treatment group (n=6)*: Mean age: 32.2±4.9 yr; Gender: males=4, females=2. *Control group (n=6):* Mean age: 31.2±5.0 yr; Gender: males=4, females=2. **Intervention:** Individuals in the treatment group had a brachioradialis (BR) to Flexor pollicis longus (FPL) transfer dorsal to radius through the interosseous membrane whereas the control group received traditional palmar BR to FPL. **Outcome Measures:** Lateral key pinch, Pronation range of motion (ROM).	1. Post-operative active pronation was significantly greater in the dorsal transfer group in comparison to the palmar group (149±6° and 75±3°, respectively). 2. Pinch strength was similar between both groups (1.28±0.16 kg and 1.20±0.21 kg), respectively. 3. It is feasible to reconstruct lateral key pinch and forearm pronation simultaneously using only the BR muscle.
Friden et al., 2012a Sweden Pre-post N=15	**Population:** Age range: 19-70 yr; Type of SCI: traumatic=12, non-traumatic=3; Level of injury: tetraplegia=15, paraplegia=0; Mean time since injury: 54.2±42.8 mo; International classification of patients' upper extremities: OCu4-OCu8.	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

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
	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).	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.
Gregersen et al., 2015 Denmark Post Test N=40	**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.	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 $p<0.001$). 5. When comparing patients who had elbow extension or pinch/thumb surgery as the only procedure, patients who had received elbow extension surgery reported significantly greater levels of satisfaction regarding ADL ($p=0.027$) and independence ($p<0.001$). 6. Patients reported that eat and drinking, grasping and coordination, dressing/undressing, stretching, and using tools were easier after surgery.
Friden et al., 2014 Sweden Case Series N=11	**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	1. Key pinch strength had improved significantly with means increasing from 0kg at pre-treatment to 1.6kg at 12m post treatment ($p<0.05$). 2. Grip strength had improved significantly with means increasing from 0kg at pre-treatment to 3.2kg at 12m post treatment ($p<0.05$). 3. Maximal distance between the thumb and index finger had improved significantly with means increasing

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
	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 digiti minimi-to-abductor pollicis brevis transfer in (n=3), carpometacarpal joint of thumb, arthrodesis (n=3), posterior deltoid-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. **Outcome Measures:** Key pinch strength, Grip strength, Maximal distance between the thumb and index finger, Anti-gravity elbow extension.	from 2.1cm at pre-treatment to 6.4cm at 12m post treatment (p<0.05). 4. Anti-gravity elbow extension was restored in one patient.
Rothwell et al., 2003 New Zealand Case Series $N_{Initial}$=29; N_{Final}=24	**Population:** Mean age: 42.9 yr; Mean time since injury: 20.5 yr; Mean time since surgery: 15.1 yr; Handedness: right=22, left=24; Level of Injury: 01: 6 hands; 02: t3 hands; 03: 5 hands; 0Cu2: 2 hands; 0Cu3: 6 hands; 0Cu4: 17 hands; 0Cu5: 8 hands; 0Cu6: 1 hand; tetraplegia. **Intervention:** Surgery. **Outcome Measures:** Lamb and Chan questionnaire with additional 10 Burwood questions, Swanson sphygmomanometer (SGM) (hook grip), Preston Pinch Meter (key pinch), Quadriplegic index of Function (QIF), Digital Analyzer (DA) (key and grip pinch).	1. Elbow Extension: bilateral surgery 9/11 subjects; Hook Grip; 17 right hands (av. Grip 46.2 mm Hg in 1991; improved slightly, not statistical significant (p=0.30)) Left hand: 15 hands: significant increase (p<0.001), av. 28.7 mmHg to 53.2 mmHg; no statistical significance between right and left hook grip as measured by SGM and DA in 2001 (p=0.93 and p=0.97). 2. Key Pinch: av. key pinch 20 right thumbs in 1991 25.8 N and decreased in time to av. 13.9 N (significant decrease p<0.001); average pinch strength 18 left thumbs decreased from 17.7-8.8 N (significant decrease p<0.001). Average pinch strength measured by DA, increase in key pinch when compared to 1991, significant for both right (p=0.01) and left (p=0.01) thumbs. 3. Active Transfer 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<0.001), 2001 data does not follow trend. 2001 DA data did not reach significance (p=0.06). 4. Longitudinal Comparison: hook grip strength 25 hands with active transfers significant increase 42.1-60.2 mm Hg (p<0.001) and pinch grip increase from 24.0-38.4 N in 31 thumbs that had active transfers using 2001 DA data (p=0.03). Hook strength obtained from a tenodesis in seven hands did not weaken over

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
		time (p=0.05) but pinch strength in 7 thumbs significantly increased (p<0.001) using 2001 DA data. 5. Questionnaire results; Lamb and Chan activity measure: showed perceived improvement of functional activities significantly lower in 2001 (p<0.001). QIF scores of current functional independence was significantly better (p=0.004). 6. Additional Burwood questionnaire showed levels of satisfaction, perceived expectation, gratification and opportunity enhancement were maintained over time (p=0.281).
Welraeds et al., 2003 Belgium Case Series N=25	**Population:** Mean age: 37 yr; Level of injury: C5-C8; Time since injury: 7-356 mo. **Intervention:** Upper limb surgery. **Outcome measures**: Functional testing.	1. No statistical analysis provided-gestural ability improved in more than 80% of the patients and functional gain was important in more than half. 2. 43 procedures; Atypical procedures (2) good: 2; Moberg procedures (18) good: 17; poor: 1; Deltoid/triceps (12) good: 7; fair 3; poor 2; Additional procedures (11) good: 7; fair: 3; poor: 1.
Freehafer 1998 USA Case Series N=285	**Population:** Level of injury: C5-C8. **Intervention:** Surgical reconstruction. **Outcome Measures:** Self-reported improvement.	1. Oponens transfers were done 180 times; transfers for finger flexion-161 times; posterior deltoid transfers-59 times; transfers for wrist extension-17 times. 2. 13 out of 285 stated that they were no better, and no patient said they were worse.
Mohammed et al., 1992 New Zealand Case Series N=57	**Population:** Mean age: 27 yr; Gender: males=51, females=6; Level of Injury: 00:4; 01: 6; 02: 4; 03: 6; 0X: 3; Cu3: 6; Cu 4: 24; Cu 5: 10; Cu 6: 3; Cu X: 3; tetraplegia. **Intervention:** Surgery. **Outcome Measures**: Activities of Daily Living (ADL), Preston Pinch Meter, Hook-grip strength, Elbow extension.	1. Subjective Assessment: obtained for 86% of the patients, av. Follow up of 37 mo (range 5-86 mo); 70% reported good or excellent results; 22% fair; 8% poor. 2. Simultaneous surgery for key-grip and hook grip strength: 96% good or excellent results. 3. Objective Results: over 70% of patients, av. follow up of 32 mo; Key Pinch 52/68 cases (76%); av. strength was 2.1 kg. Hook grip measured in 42/58 cases (72%), thumb included av. strength was 42 mmHg; thumb excluded 29 mmHg. 4. Elbow extension measured in 71% of patients, obtained grade 3 or 4 strength.
Ejeskar & Dahllof 1988 Sweden Case Series N=43	**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.	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.

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
	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.	against gravity of max. 60; 10/23 lack even more ext.; 6/7 ext. deficit greater than 60. 2. Key Grip: 50 hands/40 patients; Strength 0-3.5 kg (av. 0.7 kg); 15 cases had minimum of 1.0 kg. 3. Finger Flexion: 14 hand/13 patients (ECRL to profundi II-V); grip 0-0.27 kP (av. 0.13 kP); 5/14 minimum strength 1.0 kg. 4. 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.
Freehafer et al., 1984 USA Case Series N=68	**Population:** Age: 15-61 yr; Level of injury: tetraplegia; Time since injury: 1-17 yr. **Intervention:** Surgical reconstruction. **Outcome Measures:** Comparison of the post-surgical with the pre-surgical condition.	1. 142 transfers were performed on 68 subjects. 2. No upper limbs were made worse. 3. Four remained unimproved, all others that had tendon transfers improved.
Lamb & Chan 1983 UK Case Series N=41	**Population:** Mean age: 29 yr; Gender: males=38, females=3; Level of injury: tetraplegia; Severity of injury: complete. **Intervention:** Surgery. **Outcome Measures:** Elbow strength, Hand function (assessment checklist developed), Activities of daily living (ADL).	1. Elbow Function: 10/16 elbows (10 patients): full extension; 2/16 elbows 20-degree flexion contracture; 4/16 15 degrees of extension lag. All 10 patients considered the procedure beneficial. 2. Hand Function: 48 hands (assessed only 27 patients). 5 rated as excellent; 28 rated good; 11 rated as fair; 4 graded as poor. No patient had any impairment of hand function after operation. 3. ADL: 29 patients assessed. No one considered their functional capability deteriorated after operation. Most significant improvement in basic activities such as washing, eating and using the toilet, hold glasses and cups, wash limbs and brush hair, turn on taps, improve bladder compression, insertion of suppositories, change from complete reliance on other for self-care, more mobile, 7 able to drive a car. Improvement in UL function facilitated development of personal interests.
Hentz et al., 1983 USA Case Series N$_{Initial}$=30; N$_{Final}$=23	**Population:** Level of injury: OCu 1,2,3. **Intervention:** Reconstruction of key grip and active elbow extension.	1. No statistically significant findings reported. 2. Subjective client reports.

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
	Outcome Measures: Interview and/or questionnaire (self-care, communication, mobility), Objective measurements - pre + post op strength, Range of motion (ROM) of wrist + elbow extension, Strength of key pinch, Range of passive wrist flexion + functional testing.	

Discussion

Operative interventions on the hand and upper limb in SCI patients result in significantly improved pinch force, cylindrical grasp, and the ability to reach above shoulder height. In turn, improved motor function results 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-pinch 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 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.

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). The advantages and potential drawbacks of utilizing nerve transfers over tendon transfers are listed in Table 24. A nerve transfer utilizes a proximal foreign nerve as a donor to re-innervate and repair distal denervated targets (Addas & Midha 2009; Brown et al., 2012; Midha 2004). The function of the transferred donor nerve is sacrificed to revive function in the recipient nerve and muscles, which are considered functionally more critical than the donor nerve (Senjaya & Midha 2013). Traditionally, nerve transfers were performed for brachial plexus injuries. However, more recently the transfer of the brachialis to the anterior interosseous nerve has been applied for SCI (Hawasli et al., 2015).

Table 24 Advantages and Disadvantages of Nerve Transfers

Advantages of Nerve Transfers	Drawbacks of Nerve Transfers
• Less surgical dissection, recovery time and scarring (Brown 2012; Keith & Peljovich 2012).	• When an improperly selected donor nerve with suboptimal function is transplanted it may significantly downgrade function (Senjaya & Midha 2013).
• Only one surgical procedure to reconstruct finger flexion and extension (Revol et al., 2002; Brown 2012).	• The donating muscle may be entirely denervated and lose its function (Senjaya & Midha 2013).
• Decreased dependence on care for ADL after surgery (Bertelli et al., 2011; Brown 2012; Hentz 2002).	• Central motor re-education is challenging, especially for nerve transfers from non-synergistic nerves (Senjaya & Midha 2013).
• Less restrictive immobilization after surgery, with less pain and minimal loss of muscle function (Brown 2011; Brown 2012).	
• Greater functional gains (Brown 2011; Brown 2012; Brown et al., 2012).	
• Multiple functions may be activated by a single nerve (Brown 2011; Brown 2012; Midha 2004).	

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. 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 lastly 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 at least six months, to ensure spontaneous recovery is achieved (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).

Lastly, in order for a nerve transfer to be successful, a set of fundamental principles should be met (Senjaya & Midha, 2013; Midha et al., 2004):

1. The recipient nerve should be repaired as close as possible to the target muscle to ensure: the shortest amount of time for re-innervation, minimize distal denervation and motor end plate changes.
2. The donor nerve should be from a muscle with expendable function or redundant innervation.
3. The nerve repair should be performed directly without intervening grafts.
4. Donor muscle with pure motor fibers should be used to maximize the muscle fiber re-innervation.
5. The donor nerve should have a large number of motor axons and be a reasonable size match to the recipient nerve.
6. The donor nerve should have a synergistic function to the muscle reconstructed to facilitate motor re-education.
7. Clinicians should be mindful that motor re-education improves functional recovery post operatively.

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

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
Fox et al., 2015b USA Cohort N=7	**Population:** Mean Age: 28 yr; Gender: males=6, females=1; Level of Injury: C4=2, C5=2, C6=3; Severity of Injury: AIS A=4, AIS B=2, AIS C=1. **Intervention:** Patients receiving nerve transfer surgery completed assessments and self-reports, and were prospectively followed-up over a minimum of 12 mo. Nerve tissue was also collected during surgery. Surgeries included Brachialis (BR) to the anterior interosseous nerve (AIN; n=7), BR to the flexor carpi radialis (FCR; n=5), BR to the flexor digitorum superficialis (FDS; n=3), supinator to extensor carpi ulnaris (ECU; n=1), supinator to posterior interosseous nerve	1. Histomorphometric analysis revealed excellent functioning of the transferred nerves. 2. One patient experienced a reduced fiber density, heterogeneity of fibers, and imperfect architecture of the nerve cell after histomorphometric analysis, however, this patient was found to have low motor neuron involvement at the time of surgery. 3. No patients experienced a decline in postoperative functioning compared to baseline functioning according to MRC scores. 4. One patient who underwent deltoid-to-triceps transfer experienced

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
	(PIN; n=1), deltoid-to-triceps (n=1), and exploratory surgery (n=1). Assessments were conducted at baseline and at 2,4 and 12 wk post-surgery. **Outcome Measures:** Medical Research Council elbow flexion grade (MRC), Histomorphometric analysis, Complications post-surgery, Functional gains reported by patients.	postoperative weakness of the deltoid (MRC grade 4) but eventually subsided and strength returned to baseline levels (MRC grade 5). 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). 6. Two patients did not report any changes in functioning from pre-surgery to post-surgery. 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). 8. Two patients experienced major complications including urosepsis (n=1) and a urinary tract infection (n=1).
Bertelli et al., 2017 Brazil Pre-Post N=9	**Population:** Mean age=28±15 yr; Gender: males=8, females=1; Time since injury: 7.6±4 mo; Level of injury: C5 – C7; Severity of injury: AISA A=9. **Intervention:** Participants received nerve transfer surgery for restoration of finger flexion in 17 upper limbs of nine patients. In three upper limbs, the nerve to the brachialis was transferred to the anterior interosseous nerve (AIN). In five upper limbs, the nerve to the brachialis was transferred to median nerve motor fascicles innervating finger flexion muscles in the mid arm. In four upper limbs, the nerve to 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. **Outcome Measures**: Manual muscle test (range of finger flexion and strength).	1. A recovery of M3 or better in finger flexion strength was observed in 10 out of 17 surgically treated limbs. 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. 3. Full finger flexion with M4 strength was observed in all five upper limbs, where the ECRB was transferred to the AIN.
Bertelli et al., 2015 Brazil Post-Test N=7	**Population:** Mean age: 26 yr; Gender: males=6, females=1; Level of injury: complete C-6=7; Mean ASIA motor score: 15.8±3.9; Mean time since injury: 7 yr. **Intervention:** 27 recipient nerves. Elbow, thumb and finger extension reconstruction via nerve transfer was performed on patients with midcervical spinal cord	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

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
	injuries on average 7 mo post injury and outcomes were reported. **Outcome Measures:** British Medical Research Council scale (BMRC).	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.
Fox et al., 2018 USA Case Series N=36	**Population:** *<1 yr post SCI:* Mean age=36.1±16 yr; Gender: males=7, females=2; Time since injury: <1 yr; Level of injury: not reported; Severity of injury: not reported. *>1 yr post SCI:* Mean age=38.8±17 yr; Gender: males=22, females=5; Time since injury: >1 yr; Level of injury: not reported; Severity of injury: not reported. **Intervention:** No intervention. Medical records of patients were reviewed to develop a diagnostic algorithm, focusing on electro diagnostic studies (EDX), to determine eligibility for nerve transfer surgery based on time of injury. **Outcome Measures**: EDX data.	1. Although no statistics were reported, a substantial number of patients presenting years after SCI are candidates for nerve transfers based on EDX data.
Simcock et al., 2017 New Zealend Case Series N=53	**Population:** Age range=15 to 80 yr; Gender: males=50, females=3; Time since injury: <1 yr; Level of injury: C2 – C8; Severity of injury: AISA A=21, B=19, C=8, D=5. **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.	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 transfer surgery to improve hand opening.
Fox et al., 2015c USA Case Series N=9	**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;	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.

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
	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.	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 essential 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. 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.

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

9.0 Complementary & Alternative Medicine

Adopted from: http://www.quietcorneracupuncture.com/wp-content/uploads/2016/02/AcupunctureArm.jpg

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 26 Complementary & Alternative Medicine

Author Year Country Research Design Score Total Sample Size	Methods	Outcome
Dyson-Hudson et al., 2001 USA RCT PEDro=7 N=21	**Population:** Age: 28-69 yr; Gender: males=18, females=6; Time since injury: 5-33 yr; Length of shoulder pain: 4 mo -22 yr. **Intervention:** Subjects received either acupuncture treatments (sessions lasted 20-30 min) or Trager Psychophysical Integration - sessions lasted approx 45 min. Consisted of both table work and Mentastic® exercises (easy, natural movement sequences to enhance relaxation and decrease pain during table work). **Outcome Measures:** 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).	1. There was a significant effect of time for both treatments on performance corrected (PC)-WUSPI (Acupuncture p<0.001 and Trager p=0.001). 2. Overall a reduction of the PC-WUSPI could be seen when looking at the data from the beginning of treatment to the end for both groups (p<0.05) 3. There was a significant effect of time for both acupuncture and Trager groups for average pain & most severe pain (p<0.01, p<0.001 respectively), for the least severe pain the acupuncture group showed a significant reduction (p<0.01) compared to the Trager group. 4. Verbal response scores- there was a statistically significant treatment effect for both groups (p=0.001).

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

Dyson-Hudson et al. 2001; Trager Psychophysical Integration

PC-WUSPI 0.51 (-0.43,1.45)

ROM - internal rotation at 90° (IR90) 0.36 (-0.57,1.29)

Favours Control — SMD (95%C.I.) — Favours Treatment

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

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

Wong et al. 2003; Acupuncture

ASIA - motor: 1.01 (0.59,1.43)
ASIA - pinprick: 0.70 (0.30,1.11)
ASIA - light tough: 0.77 (0.36,1.18)
FIM: 0.83 (0.42,1.24)

Favours Control — Standardized Mean Difference (95%C.I.) — Favours Treatment
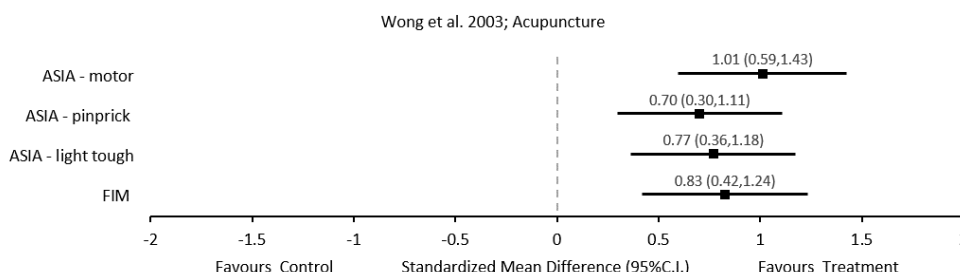
Discussion

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 15) 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 proximial/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 retrospectrive 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-pinch 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.

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.

References

Ada, L., Dorsch, S., & Canning, C. G. (2006). Strengthening interventions increase strength and improve activity after stroke: a systematic review. *Australian Journal of Physiotherapy*, *52*(4), 241-248.

Addas, B. M., & Midha, R. (2009). Nerve transfers for severe nerve injury. *Neurosurgery clinics of North America*, *20*(1), 27-38.

Ahuja, C. S., Nori, S., Tetreault, L., Wilson, J., Kwon, B., Harrop, J., ... & Fehlings, M. G. (2017). Traumatic spinal cord injury—repair and regeneration. *Neurosurgery*, *80*(3S), S9-S22.

Alon, G., & McBride, K. (2003). Persons with C5 or C6 tetraplegia achieve selected functional gains using a neuroprosthesis. *Archives of physical medicine and rehabilitation*, *84*(1), 119-124.

Anderson, K. D. (2004). Targeting recovery: priorities of the spinal cord-injured population. *Journal of neurotrauma*, *21*(10), 1371-1383.

Anderson, K. D., Fridén, J., & Lieber, R. L. (2009). Acceptable benefits and risks associated with surgically improving arm function in individuals living with cervical spinal cord injury. *Spinal Cord*, *47*(4), 334.

Athanasiou, A., Terzopoulos, N., Pandria, N., Xygonakis, I., Foroglou, N., Polyzoidis, K., & Bamidis, P. D. (2018). Functional brain connectivity during multiple motor imagery tasks in spinal cord injury. *Neural plasticity*, *2018*.

Baker, L. L., McNeal, D. R., Benton, L. A., Bowman, B. R., & Waters, R. L. (1993). NeuroMuscular Electrical Stimulation: A Practical Guide. Downey, CA: Los Amigos Research and Education Institute.

Backus, D. (2010). Exploring the potential for neural recovery after incomplete tetraplegia through nonsurgical interventions. *PM&R*, *2*(12), S279-S285.

Backus, D., Cordo, P., Gillott, A., Kandilakis, C., Mori, M., & Raslan, A. M. (2014). Assisted movement with proprioceptive stimulation reduces impairment and restores function in incomplete spinal cord injury. *Archives of physical medicine and rehabilitation*, *95*(8), 1447-1453.

Barlow, J., Wright, C., Sheasby, J., Turner, A., & Hainsworth, J. (2002). Self-management approaches for people with chronic conditions: a review. *Patient education and counseling*, *48*(2), 177-187.

Bedbrook, G. M. (2013). *The care and management of spinal cord injuries*. Springer Science & Business Media.

Beekhuizen, K. S. (2005). New perspectives on improving upper extremity function after spinal cord injury. *Journal of Neurologic Physical Therapy*, *29*(3), 157-162.

Beekhuizen, K. S., & Field-Fote, E. C. (2008). Sensory stimulation augments the effects of massed practice training in persons with tetraplegia. *Archives of physical medicine and rehabilitation*, *89*(4), 602-608.

Bekhet, A. H., Bochkezanian, V., Saab, I. M., & Gorgey, A. S. (2019). The effects of electrical stimulation parameters in managing spasticity after spinal cord injury: a systematic review. *American journal of physical medicine & rehabilitation*, *98*(6), 484-499.

Belci, M., Catley, M., Husain, M., Frankel, H. L., & Davey, N. J. (2004). Magnetic brain stimulation can improve clinical outcome in incomplete spinal cord injured patients. *Spinal cord*, *42*(7), 417.

Bennett, M. I., Bagnall, A. M., & José Closs, S. (2009). How effective are patient-based educational interventions in the management of cancer pain? Systematic review and meta-analysis. Pain, 143(3), 192–199.

Bernet, M., Sommerhalder, K., Mischke, C., Hahn, S., & Wyss, A. (2018). *"Theory Does Not Get You From Bed to Wheelchair." Rehabilitation Nursing, 1*.doi:10.1097/rnj.0000000000000175

Bertelli, J. A., Ghizoni, M. F., & Tacca, C. P. (2011). Transfer of the teres minor motor branch for triceps reinnervation in tetraplegia: case report. *Journal of neurosurgery*, *114*(5), 1457-1460.

Bertelli, J. A., & Ghizoni, M. F. (2017). Nerve transfers for restoration of finger flexion in patients with tetraplegia. *Journal of Neurosurgery: Spine*, *26*(1), 55-61.

Bertelli, J. A., & Ghizoni, M. F. (2015). Nerve transfers for elbow and finger extension reconstruction in midcervical spinal cord injuries. *Journal of neurosurgery*, *122*(1), 121-127.

Birbaumer, N., Murguialday, A. R., & Cohen, L. (2008). Brain–computer interface in paralysis. *Current opinion in neurology*, *21*(6), 634-638.

Bizzi, E., Cheung, V. C. K., d'Avella, A., Saltiel, P., & Tresch, M. (2008). Combining modules for movement. *Brain research reviews*, *57*(1), 125-133.

Blabe, C. H., Gilja, V., Chestek, C. A., Shenoy, K. V., Anderson, K. D., & Henderson, J. M. (2015). Assessment of brain–machine interfaces from the perspective of people with paralysis. *Journal of neural engineering*, *12*(4), 043002.

Blackburn, J. (2003). Trager® psychophysical integration–an overview. *Journal of Bodywork and Movement Therapies*, *7*(4), 233-239.

Borges, L. R., Fernandes, A. B., Melo, L. P., Guerra, R. O., & Campos, T. F. (2018). Action observation for upper limb rehabilitation after stroke. Cochrane Database of Systematic Reviews, 21(10), 234-244.

Bradbury, E. J., Moon, L. D., Popat, R. J., King, V. R., Bennett, G. S., Patel, P. N., ... & McMahon, S. B. (2002). Chondroitinase ABC promotes functional recovery after spinal cord injury. *Nature*, *416*(6881), 636.

Brown, J. M. (2011). Nerve transfers in tetraplegia I: background and technique. *Surgical neurology international*, *2*.

Brown, J. M. (2012). *The reconstructive neurosurgery of spinal cord injury* (pp. 134-168). New York: Oxford University Press.

Brown, J. M., Vivio, N., & Sheean, G. L. (2012). The clinical practice of reconstructive neurosurgery. *Clinical neurology and neurosurgery*, *114*(5), 506-514.

Brucker, B. S., & Buylaeva, N. V. (1996). Biofeedback effect on electromyography responses in patients with spinal cord injury. *Archives of Physical Medicine and Rehabilitation*, *77*(2), 133-137.

Bryden, A. M., Memberg, W. D., & Crago, P. E. (2000). Electrically stimulated elbow extension in persons with C5/C6 tetraplegia: a functional and physiological evaluation. *Archives of physical medicine and rehabilitation*, *81*(1), 80-88.

Bryden, A. M., Kilgore, K. L., Lind, B. B., & David, T. Y. (2004). Triceps denervation as a predictor of elbow flexion contractures in C5 and C6 tetraplegia. *Archives of physical medicine and rehabilitation*, *85*(11), 1880-1885.

Bryden, A., Sinnott, A., & Mulcahey, M. J. (2005). Innovative strategies for improving upper extremity function in tetraplegia and considerations in measuring functional outcomes. *Topics in Spinal Cord Injury Rehabilitation*, *10*(4), 75-93.

Buchli, A. D., & Schwab, M. E. (2005). Inhibition of Nogo: a key strategy to increase regeneration, plasticity and functional recovery of the lesioned central nervous system. *Annals of medicine*, *37*(8), 556-567.

Bunday, K. L., Tazoe, T., Rothwell, J. C., & Perez, M. A. (2014). Subcortical control of precision grip after human spinal cord injury. *Journal of Neuroscience*, *34*(21), 7341-7350.

Bunday, K. L., Urbin, M. A., & Perez, M. A. (2018). Potentiating paired corticospinal-motoneuronal plasticity after spinal cord injury. *Brain stimulation*, *11*(5), 1083-1092.

Burns, A. S., & Meythaler, J. M. (2001). Intrathecal baclofen in tetraplegia of spinal origin: efficacy for upper extremity hypertonia. *Spinal Cord*, *39*(8), 413.

Cameron, T., Breton, J. G., Needham-Shropshire, B., & Klose, K. J. (1998). An upper body exercise system incorporating resistive exercise and neuromuscular electrical stimulation (NMS). *The journal of spinal cord medicine*, *21*(1), 1-6.

Cameron, T., Loeb, G. E., Peck, R. A., Schulman, J. H., Strojnik, P., & Troyk, P. R. (1997). Micromodular implants to provide electrical stimulation of paralyzed muscles and limbs. *IEEE Transactions on Biomedical Engineering*, *44*(9), 781-790.

Cappello, L., Meyer, J. T., Galloway, K. C., Peisner, J. D., Granberry, R., Wagner, D. A., ... & Walsh, C. J. (2018). Assisting hand function after spinal cord injury with a fabric-based soft robotic glove. *Journal of neuroengineering and rehabilitation*, *15*(1), 59.

Carlson, M. J., & Krahn, G. (2006). Use of complementary and alternative medicine practitioners by people with physical disabilities: estimates from a National US Survey. *Disability and rehabilitation*, *28*(8), 505-513.

Carroll, S., Coope, C., Brown, D., Sormann, G., Flood, S., & Denison, M. (2000). Australian Experience with the Freehand System® for Restoring Graspin Quadriplegia. *Australian and New Zealand Journal of Surgery*, *70*(8), 563-568.

Cheung, V. C., d'Avella, A., Tresch, M. C., & Bizzi, E. (2005). Central and sensory contributions to the activation and organization of muscle synergies during natural motor behaviors. *Journal of Neuroscience*, *25*(27), 6419-6434.

Coignard, P., Departe, J. P., Neris, O. R., Baillet, A., Bar, A., Drean, D., ... & Le Guiet, J. L. (2013). ANSO study: evaluation in an indoor environment of a mobile assistance robotic grasping arm. *Annals of physical and rehabilitation medicine*, *56*(9-10), 621-633.

Collinger, J. L., Boninger, M. L., Bruns, T. M., Curley, K., Wang, W., & Weber, D. J. (2013). Functional priorities, assistive technology, and brain-computer interfaces after spinal cord injury. *Journal of rehabilitation research and development*, *50*(2), 145.

Coster, S., & Norman, I. (2009). Cochrane reviews of educational and self-management interventions to guide nursing practice: A review. International Journal of Nursing Studies, 46(4), 508–528.

Côté, M. P., Azzam, G. A., Lemay, M. A., Zhukareva, V., & Houlé, J. D. (2011). Activity-dependent increase in neurotrophic factors is associated with an enhanced modulation of spinal reflexes after spinal cord injury. *Journal of neurotrauma*, *28*(2), 299-309.

Cortes, M., Elder, J., Rykman, A., Murray, L., Avedissian, M., Stampas, A., ... & Edwards, D. J. (2013). Improved motor performance in chronic spinal cord injury following upper-limb robotic training. *NeuroRehabilitation*, *33*(1), 57-65.

Cortes, M., Medeiros, A. H., Gandhi, A., Lee, P., Krebs, H. I., Thickbroom, G., & Edwards, D. (2017). Improved grasp function with transcranial direct current stimulation in chronic spinal cord injury. *NeuroRehabilitation*, *41*(1), 51-59.

Coulet, B., Allieu, Y., & Chammas, M. (2002). Injured metamere and functional surgery of the tetraplegic upper limb. *Hand clinics*, *18*(3), 399-412.

Coulet, B., Waitzenegger, T., Teissier, J., Lazerges, C., Chammas, M., Fattal, C., & Cambon-Binder, A. (2018). Arthrodesis Versus Carpometacarpal Preservation in Key-Grip Procedures in Tetraplegic Patients: A Comparative Study of 40 Cases. *The Journal of hand surgery*, *43*(5), 483-e1.

Courtine, G., & Sofroniew, M. V. (2019). Spinal cord repair: advances in biology and technology. *Nature medicine*, 1.

Colyer, R. A., & Kappelman, B. O. N. N. I. E. (1981). Flexor pollicis longus tenodesis in tetraplegia at the sixth cervical level. A prospective evaluation of functional gain. *The Journal of bone and joint surgery. American volume*, *63*(3), 376-379.

Crane, D. A., Hoffman, J. M., & Reyes, M. R. (2017). Benefits of an exercise wellness program after spinal cord injury. *The journal of spinal cord medicine*, *40*(2), 154-158.

Curt, A., Van Hedel, H. J., Klaus, D., Dietz, V., & EM-SCI study group. (2008). Recovery from a spinal cord injury: significance of compensation, neural plasticity, and repair. *Journal of neurotrauma*, *25*(6), 677-685.

Curtin, M. (1994). Development of a tetraplegic hand assessment and splinting protocol. *Spinal Cord*, *32*(3), 159.

Curtin, C. M., Gater, D. R., & Chung, K. C. (2005). Upper extremity reconstruction in the tetraplegic population, a national epidemiologic study. *The Journal of hand surgery*, *30*(1), 94-99.
Curtis, K. A., Tyner, T. M., Zachary, L., Lentell, G., Brink, D., Didyk, T., ... & Lesina, S. (1999). Effect of a standard exercise protocol on shoulder pain in long-term wheelchair users. *Spinal cord*, *37*(6), 421.

Dalyan, M., Sherman, A., & Cardenas, D. D. (1998). Factors associated with contractures in acute spinal cord injury. *Spinal Cord*, *36*(6), 405.

d'Avella, A., Saltiel, P., & Bizzi, E. (2003). Combinations of muscle synergies in the construction of a natural motor behavior. *Nature neuroscience*, *6*(3), 300.

Deakin, T. A., McShane, C. E., Cade, J. E., & Williams, R. (2005). Group based training for self-management strategies in people with type 2 diabetes mellitus. *Cochrane database of systematic reviews*, (2).

Dias, P., Silva, R., Amorim, P., Laíns, J., Roque, E., Serôdio, I., ... & Potel, M. (2019). Using Virtual Reality to Increase Motivation in Poststroke Rehabilitation. IEEE Computer Graphics and Applications, 39(1), 64-70.

Dietz, V., & Fouad, K. (2013). Restoration of sensorimotor functions after spinal cord injury. *Brain*, *137*(3), 654-667.

Dimbwadyo-Terrer, I., de los Reyes-Guzmán, A., Bernal-Sahún, A., López-Monteagudo, P., Trincado-Alonso, F., Polonio-López, B., & Gil-Agudo, Á. (2013). Virtual reality system toyra: a new tool to assess and treatment for upper limb motor impairment in patients with spinal cord injury. In *Converging Clinical and Engineering Research on Neurorehabilitation* (pp. 853-858). Springer, Berlin, Heidelberg.

Dimbwadyo-Terrer, I., Gil-Agudo, A., Segura-Fragoso, A., de los Reyes-Guzmán, A., Trincado-Alonso, F., Piazza, S., & Polonio-López, B. (2016). Effectiveness of the virtual reality system Toyra on upper limb function in people with tetraplegia: a pilot randomized clinical trial. *BioMed research international*, *2016*.

Dimbwadyo-Terrer, I., Trincado-Alonso, F., de los Reyes-Guzmán, A., Aznar, M. A., Alcubilla, C., Pérez-Nombela, S., ... & Gil-Agudo, A. (2016). Upper limb rehabilitation after spinal cord injury: a treatment based on a data glove and an immersive virtual reality environment. *Disability and Rehabilitation: Assistive Technology*, *11*(6), 462-467.

Dimbwadyo-Terrer, I., Trincado-Alonso, F., De los Reyes-Guzmán, A., López-Monteagudo, P., Polonio-López, B., & Gil-Agudo, A. (2016). Activities of daily living assessment in spinal cord injury using the virtual reality system Toyra®: functional and kinematic correlations. *Virtual Reality*, *20*(1), 17-26.

DiPasquale-Lehnerz, P. (1994). Orthotic intervention for development of hand function with C-6 quadriplegia. *American Journal of Occupational Therapy*, *48*(2), 138-144.

Di Rienzo, F., Guillot, A., Mateo, S., Daligault, S., Delpuech, C., Rode, G., & Collet, C. (2014). Neuroplasticity of prehensile neural networks after quadriplegia. *Neuroscience*, *274*, 82-92.

Di Rienzo, F., Guillot, A., Mateo, S., Daligault, S., Delpuech, C., Rode, G., & Collet, C. (2015). Neuroplasticity of imagined wrist actions after spinal cord injury: a pilot study. *Experimental brain research*, *233*(1), 291-302.

Ditunno Jr, J. F. (1999). Predicting recovery after spinal cord injury: a rehabilitation imperative. *Archives of physical medicine and rehabilitation*, *80*(4), 361-364.

Drolet, M., Noreau, L., Vachon, J., & Moffet, H. (1999). Muscle strength changes as measured by dynamometry following functional rehabilitation in individuals with spinal cord injury. *Archives of Physical Medicine and Rehabilitation*, *80*(7), 791-800.

Dunkerley, A. L., Ashburn, A., & Stack, E. L. (2000). Deltoid triceps transfer and functional independence of people with tetraplegia. *Spinal Cord*, *38*(7), 435.

Dunn, J. A., Hay-Smith, E. J. C., Whitehead, L. C., & Keeling, S. (2012). Issues influencing the decision to have upper limb surgery for people with tetraplegia. *Spinal Cord*, *50*(11), 844.

Dunn, J. A., Rothwell, A. G., Mohammed, K. D., & Sinnott, K. A. (2014). The effects of aging on upper limb tendon transfers in patients with tetraplegia. *The Journal of hand surgery*, *39*(2), 317-323.

Dunn, J. A., Mohammed, K. D., Beadel, G. P., Rothwell, A. G., & Simcock, J. W. (2017). A comparative outcome study of hamstring versus tibialis anterior and synthetic grafts for deltoid to triceps transfers. *The Journal of hand surgery*, *42*(10), 833-e1.

Dyson-Hudson, T. A., Shiflett, S. C., Kirshblum, S. C., Bowen, J. E., & Druin, E. L. (2001). Acupuncture and Trager psychophysical integration in the treatment of wheelchair user's shoulder pain in individuals with spinal cord injury. *Archives of physical medicine and rehabilitation*, *82*(8), 1038-1046.

Ejeskär, A., & Dahllöf, A. (1988). Results of reconstructive surgery in the upper limb of tetraplegic patients. *Spinal Cord*, *26*(3), 204.

Ertelt, D., Small, S., Solodkin, A., Dettmers, C., McNamara, A., Binkofski, F., & Buccino, G. (2007). Action observation has a positive impact on rehabilitation of motor deficits after stroke. Neuroimage, 36, T164-T173.

Evans, N., Wingo, B., Sasso, E., Hicks, A., Gorgey, A. S., & Harness, E. (2015). Exercise recommendations and considerations for persons with spinal cord injury. *Archives of physical medicine and rehabilitation*, *96*(9), 1749-1750.

Failla, J. M., Peimer, C. A., & Sherwin, F. S. (1990). Brachioradialis transfer for digital palsy. *Journal of Hand Surgery*, *15*(3), 312-316.

Fan, Q., Cavus, O., Xiong, L., & Xia, Y. (2018). Spinal Cord Injury: How Could Acupuncture Help?. *Journal of acupuncture and meridian studies*, *11*(4), 124-132.

Flinn, N.A., Radomski, M. V., & Latham, C. A. T. (Eds.). (2008). *Occupational therapy for physical dysfunction.* Lippincott Williams & Wilkins.

Foldes, S. T., Weber, D. J., & Collinger, J. L. (2015). MEG-based neurofeedback for hand rehabilitation. *Journal of neuroengineering and rehabilitation*, *12*(1), 85.

Forner-Cordero, I., Mudarra-Garcia, J., Forner-Valero, J. V., & Vilar-De-La-Pena, R. (2003). The role of upper limb surgery in tetraplegia. *Spinal Cord*, *41*(2), 90.

Fox, P. M., Suarez, P., Hentz, V. R., & Curtin, C. M. (2015a). Access to surgical upper extremity care for people with tetraplegia: an international perspective. *Spinal cord*, *53*(4), 302.

Fox, I. K., Davidge, K. M., Novak, C. B., Hoben, G., Kahn, L. C., Juknis, N., ... & Mackinnon, S. E. (2015b). Nerve transfers to restore upper extremity function in cervical spinal cord injury: update and preliminary outcomes. *Plastic and reconstructive surgery*, *136*(4), 780-792.

Fox, I. K., Davidge, K. M., Novak, C. B., Hoben, G., Kahn, L. C., Juknis, N., ... & Mackinnon, S. E. (2015c). Use of peripheral nerve transfers in tetraplegia: Evaluation of feasibility and morbidity. *Hand*, *10*(1), 60-67.

Fox, I. K., Novak, C. B., Krauss, E. M., Hoben, G. M., Zaidman, C. M., Ruvinskaya, R., ... & Mackinnon, S. E. (2018). The use of nerve transfers to restore upper extremity function in cervical spinal cord injury. *PM&R*, *10*(11), 1173-1184.

Freehafer, A. A., Kelly, C. M., & Peckham, P. H. (1984). Tendon transfer for the restoration of upper limb function after a cervical spinal cord injury. *The Journal of hand surgery*, *9*(6), 887-893.

Freehafer, A. A. (1998). Tendon transfers in tetraplegic patients: the Cleveland experience. *Spinal Cord*, *36*(5), 315.

Friedenberg, Z. B. (1954). Transposition of the biceps brachii for triceps weakness. *JBJS*, *36*(3), 656-658.

Fridén, J., Gohritz, A., Turcsányi, I., & Ejeskär, A. (2012). Restoration of active palmar abduction of the thumb in tetraplegia by tendon transfer of the extensor digiti minimi to abductor pollicis brevis. *Journal of Hand Surgery (European Volume)*, *37*(7), 665-672.

Fridén, J., Reinholdt, C., Gohritz, A., Peace, W. J., Ward, S. R., & Lieber, R. L. (2012). Simultaneous powering of forearm pronation and key pinch in tetraplegia using a single muscle-tendon unit. *Journal of Hand Surgery (European Volume)*, *37*(4), 323-328.

Fridén, J., Reinholdt, C., Wangdell, J., & Gohritz, A. (2014). Upper extremity reconstruction in non-traumatic spinal cord injuries: an under-recognized opportunity. *Journal of rehabilitation medicine*, *46*(1), 33-38.

Frullo, J. M., Elinger, J., Pehlivan, A. U., Fitle, K., Nedley, K., Francisco, G. E., ... & O'Malley, M. K. (2017). Effects of assist-as-needed upper extremity robotic therapy after incomplete spinal cord injury: a parallel-group controlled trial. *Frontiers in neurorobotics*, *11*, 26.

Gad, P., Lee, S., Terrafranca, N., Zhong, H., Turner, A., Gerasimenko, Y., & Edgerton, V. R. (2018). Non-invasive activation of cervical spinal networks after severe paralysis. *Journal of neurotrauma*, *35*(18), 2145-2158.

Fridén, J., Reinholdt, C., Wangdell, J., & Gohritz, A. (2014). Upper extremity reconstruction in non-traumatic spinal cord injuries: an under-recognized opportunity. *Journal of rehabilitation medicine*, *46*(1), 33-38.

Frullo, J. M., Elinger, J., Pehlivan, A. U., Fitle, K., Nedley, K., Francisco, G. E., ... & O'Malley, M. K. (2017). Effects of assist-as-needed upper extremity robotic therapy after incomplete spinal cord injury: a parallel-group controlled trial. *Frontiers in neurorobotics*, *11*, 26.

Gad, P., Lee, S., Terrafranca, N., Zhong, H., Turner, A., Gerasimenko, Y., & Edgerton, V. R. (2018). Non-invasive activation of cervical spinal networks after severe paralysis. *Journal of neurotrauma*, *35*(18), 2145-2158.

Gant, K. L., Nagle, K. G., Cowan, R. E., Field-Fote, E. C., Nash, M. S., Kressler, J., ... & Anderson, K. D. (2018). Body system effects of a multi-modal training program targeting chronic, motor complete thoracic spinal cord injury. *Journal of neurotrauma*, *35*(3), 411-423.

Gansel, J. O. H. N., Waters, R., & Gellman, H. (1990). Transfer of the pronator teres tendon to the tendons of the flexor digitorum profundus in tetraplegia. *The Journal of bone and joint surgery. American volume*, *72*(3), 427-432.

Gibson, P. G., Powell, H., Wilson, A., Abramson, M. J., Haywood, P., Bauman, A., … Roberts, J. J. L. (2009). Self-management education and regular practitioner review for adults with asthma. The Cochrane Database of Systematic Reviews

Gomes-Osman, J., & Field-Fote, E. C. (2015). Cortical vs. afferent stimulation as an adjunct to functional task practice training: a randomized, comparative pilot study in people with cervical spinal cord injury. *Clinical rehabilitation*, *29*(8), 771-782.

Gomes-Osman, J., & Field-Fote, E. C. (2013). Bihemispheric anodal corticomotor stimulation using transcranial direct current stimulation improves bimanual typing task performance. *Journal of motor behavior*, *45*(4), 361-367.

Gomes-Osman, J., & Field-Fote, E. C. (2015). Improvements in hand function in adults with chronic tetraplegia following a multi-day 10Hz rTMS intervention combined with repetitive task practice. *Journal of neurologic physical therapy: JNPT*, *39*(1), 23.

Gomes-Osman, J., Tibbett, J. A., Poe, B. P., & Field-Fote, E. C. (2017). Priming for improved hand strength in persons with chronic tetraplegia: a comparison of priming-augmented functional task practice, priming alone, and conventional exercise training. *Frontiers in neurology*, *7*, 242.

Gómez-Pinilla, F., Ying, Z., Roy, R. R., Molteni, R., & Edgerton, V. R. (2002). Voluntary exercise induces a BDNF-mediated mechanism that promotes neuroplasticity. *Journal of neurophysiology*, *88*(5), 2187-2195.

Gregersen, H., Lybæk, M., Lauge Johannesen, I., Leicht, P., Nissen, U. V., & Biering-Sørensen, F. (2015). Satisfaction with upper extremity surgery in individuals with tetraplegia. *The journal of spinal cord medicine*, *38*(2), 161-169.

Grover, J., Gellman, H., & Waters, R. L. (1996). The effect of a flexion contracture of the elbow on the ability to transfer in patients who have quadriplegia at the sixth cervical level. *JBJS*, *78*(9), 1397-1400.

Forner-Cordero, I., Mudarra-Garcia, J., Forner-Valero, J. V., & Vilar-De-La-Pena, R. (2003). The role of upper limb surgery in tetraplegia. *Spinal Cord*, *41*(2), 90.

Haisma, J. A., Bussmann, J. B., Stam, H. J., Sluis, T. A., Bergen, M. P., Dallmeijer, A. J., ... & van der Woude, L. H. (2006). Changes in physical capacity during and after inpatient rehabilitation in subjects with a spinal cord injury. *Archives of physical medicine and rehabilitation*, *87*(6), 741-748.

Hanson, R. W., & Franklin, M. R. (1976). Sexual loss in relation to other functional losses for spinal cord injured males. *Archives of physical medicine and rehabilitation*, *57*(6), 291-293.

Harvey, L. (1996). Principles of conservative management for a non-orthotic tenodesis grip in tetraplegics. *Journal of Hand Therapy*, *9*(3), 238-242.

Harvey, L., de Jong, I., Goehl, G., & Marwedel, S. (2006). Twelve weeks of nightly stretch does not reduce thumb web-space contractures in people with a neurological condition: a randomised controlled trial. *Australian Journal of Physiotherapy*, *52*(4), 251-258.

Harvey, L. A., Dunlop, S. A., Churilov, L., Galea, M. P., Hands, S. C. I. P. A. S., & Collaborators, O. T. (2016). Early intensive hand rehabilitation is not more effective than usual care plus one-to-one hand therapy in people with sub-acute spinal cord injury ('Hands On'): a randomised trial. *Journal of physiotherapy*, *62*(2), 88-95.

Hawasli, A. H., Chang, J., Reynolds, M. R., & Ray, W. Z. (2015). Transfer of the brachialis to the anterior interosseous nerve as a treatment strategy for cervical spinal cord injury. *Global spine journal*, *5*(02), 110-117.

Hentz, V. R., Brown, M., & Keoshian, L. A. (1983). Upper limb reconstruction in quadriplegia: functional assessment and proposed treatment modifications. *The Journal of hand surgery*, *8*(2), 119-131.

Hentz, V. R. (2002). Surgical strategy: matching the patient with the procedure. *Hand clinics*, *18*(3), 503-518.
Hicks, A. L., Martin, K. A., Ditor, D. S., Latimer, A. E., Craven, C., Bugaresti, J., & McCartney, N. (2003). Long-term exercise training in persons with spinal cord injury: effects on strength, arm ergometry performance and psychological well-being. *Spinal cord*, *41*(1), 34.

Hincapie, J. G., Blana, D., Chadwick, E. K., & Kirsch, R. F. (2008). Musculoskeletal model-guided, customizable selection of shoulder and elbow muscles for a C5 SCI neuroprosthesis. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *16*(3), 255-263.

Hobby J, Taylor PN, Esnouf J. Restoration of tetraplegic hand function by use of the neurocontrol Freehand System. J Hand Surg Br 2001;26B:459-64.

Hodkin, E. F., Lei, Y., Humby, J., Glover, I. S., Choudhury, S., Kumar, H., ... & Jackson, A. (2018). Automated FES for upper limb rehabilitation following stroke and spinal cord injury. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *26*(5), 1067-1074.

Hoffman, H., Sierro, T., Niu, T., Sarino, M. E., Sarrafzadeh, M., McArthur, D., ... & Lu, D. C. (2017). Rehabilitation of hand function after spinal cord injury using a novel handgrip device: a pilot study. *Journal of neuroengineering and rehabilitation*, *14*(1), 22.

Hoffman, L., & Field-Fote, E. (2013). Effects of practice combined with somatosensory or motor stimulation on hand function in persons with spinal cord injury. *Topics in spinal cord injury rehabilitation*, *19*(4), 288-299.

Hoshimiya, N. (1989). A master-slave type multichannel functional electrical stimulation (FES) system for the control of the paralyzed upper extremities. *Automedia*, *11*, 209-220.

Houle, J. D., Morris, K., Skinner, R. D., Garcia-Rill, E., & Peterson, C. A. (1999). Effects of fetal spinal cord tissue transplants and cycling exercise on the soleus muscle in spinalized rats. *Muscle & Nerve: Official Journal of the American Association of Electrodiagnostic Medicine*, *22*(7), 846-856.

House, J. H., Comadoll, J., & Dahl, A. L. (1992). One-stage key pinch and release with thumb carpal-metacarpal fusion in tetraplegia. *The Journal of hand surgery*, *17*(3), 530-538.

Howlett, O. A., Lannin, N. A., Ada, L., & McKinstry, C. (2015). Functional electrical stimulation improves activity after stroke: a systematic review with meta-analysis. *Archives of physical medicine and rehabilitation*, *96*(5), 934-943.

Hummel, J. M., Snoek, G. J., van Til, J. A., van Rossum, W., & IJzerman, M. J. (2005). A multicriteria decision analysis of augmentative treatment of upper limbs in persons with tetraplegia. *Journal of rehabilitation research and development*, *42*(5), 635.

Iwahashi, K., Hayashi, T., Watanabe, R., Nishimura, A., Ueta, T., Maeda, T., & Shiba, K. (2017). Effects of orthotic therapeutic electrical stimulation in the treatment of patients with paresis associated with acute cervical spinal cord injury: A randomized control trial. *Spinal cord*, *55*(12), 1066.

James, N. D., McMahon, S. B., Field-Fote, E. C., & Bradbury, E. J. (2018). Neuromodulation in the restoration of function after spinal cord injury. *The Lancet Neurology*, *17*(10), 905-917.

Jarus, T. (1994). Motor learning and occupational therapy: The organization of practice. *American Journal of Occupational Therapy*, *48*(9), 810-816.

Johnstone, B. R., Jordan, C. J., & Buntine, J. A. (1988). A review of surgical rehabilitation of the upper limb in quadriplegia. *Spinal Cord*, *26*(5), 317.

Keith, M. W., & Lacey, S. H. (1991). Surgical rehabilitation of the tetraplegic upper extremity. *Journal of Neurologic Rehabilitation*, *5*(1-2), 75-87.

Keith, M. W., & Peljovich, A. (2012). Surgical treatments to restore function control in spinal cord injury. In *Handbook of clinical neurology* (Vol. 109, pp. 167-179). Elsevier.

Kelly, C. M., Freehafer, A. A., Peckham, P. H., & Stroh, K. (1985). Postoperative results of opponensplasty and flexor tendon transfer in patients with spinal cord injuries. *The Journal of hand surgery*, *10*(6), 890-894.

Kilduski, N. C., & Rice, M. S. (2003). Qualitative and quantitative knowledge of results: effects on motor learning. *American Journal of Occupational Therapy*, *57*(3), 329-336.

Kilgore, K. L., Peckham, P. H., Keith, M. W., Thrope, G. B., Wuolle, K. S., Bryden, A. M., & Hart, R. L. (1997). An implanted upper-extremity neuroprosthesis. Follow-up of five patients. *JBJS*, *79*(4), 533-41.

Kilgore, K. L., Hoyen, H. A., Bryden, A. M., Hart, R. L., Keith, M. W., & Peckham, P. H. (2008). An implanted upper-extremity neuroprosthesis using myoelectric control. *The Journal of hand surgery*, *33*(4), 539-550.

Kilgore, K. L., Bryden, A., Keith, M. W., Hoyen, H. A., Hart, R. L., Nemunaitis, G. A., & Peckham, P. H. (2018). Evolution of neuroprosthetic approaches to restoration of upper extremity function in spinal cord injury. *Topics in spinal cord injury rehabilitation*, *24*(3), 252-264.

Kim, B., In, H., Lee, D. Y., & Cho, K. J. (2017). Development and assessment of a hand assist device: GRIPIT. *Journal of neuroengineering and rehabilitation*, *14*(1), 15.

Kim, E., & Kim, K. (2015). Effect of purposeful action observation on upper extremity function in stroke patients. *Journal of physical therapy science*, *27*(9), 2867-2869.

Kimberley, T. J., Lewis, S. M., Auerbach, E. J., Dorsey, L. L., Lojovich, J. M., & Carey, J. R. (2004). Electrical stimulation driving functional improvements and cortical changes in subjects with stroke. *Experimental Brain Research*, *154*(4), 450-460.

Kirshblum, S., Millis, S., McKinley, W., & Tulsky, D. (2004). Late neurologic recovery after traumatic spinal cord injury. *Archives of physical medicine and rehabilitation*, *85*(11), 1811-1817.

Kirshblum, S., & Lin, V. W. (Eds.). (2018). *Spinal cord medicine.* Springer Publishing Company. Klamroth-Marganska, V., Blanco, J., Campen, K., Curt, A., Dietz, V., Ettlin, T., ... & Luft, A. (2014). Three-dimensional, task-specific robot therapy of the arm after stroke: a multicentre, parallel-group randomised trial. The Lancet Neurology, 13(2), 159-166.

Klose, K. J., Needham, B. M., Schmidt, D., Broton, J. G., & Green, B. A. (1993). An assessment of the contribution of electromyographic biofeedback as an adjunct therapy in the physical training of spinal cord injured persons. *Archives of physical medicine and rehabilitation*, *74*(5), 453-456.

Knutson, J. S., Makowski, N. S., Kilgore, K. L., & Chae, J. (2019). Neuromuscular Electrical Stimulation Applications. In *Atlas of Orthoses and Assistive Devices* (pp. 432-439). Content Repository Only!.

Kohlmeyer, K. M., Hill, J. P., Yarkony, G. M., & Jaeger, R. J. (1996). Electrical stimulation and biofeedback effect on recovery of tenodesis grasp: a controlled study. *Archives of physical medicine and rehabilitation*, *77*(7), 702-706.

Kozin, S.H. (2002). Tetraplegia. J Hand Surg Am, 2(3):141-52.

Kozin, S. H., D'Addesi, L., Chafetz, R. S., Ashworth, S., & Mulcahey, M. J. (2010). Biceps-to-triceps transfer for elbow extension in persons with tetraplegia. *The Journal of hand surgery*, *35*(6), 968-975.

Krajnik, S. R., & Bridle, M. J. (1992). Hand splinting in quadriplegia: current practice. *American Journal of Occupational Therapy*, *46*(2), 149-156.

Krucoff, M. O., Rahimpour, S., Slutzky, M. W., Edgerton, V. R., & Turner, D. A. (2016). Enhancing nervous system recovery through neurobiologics, neural interface training, and neurorehabilitation. *Frontiers in neuroscience*, *10*, 584.

Kuk, E. J., Kim, J. M., Oh, D. W., & Hwang, H. J. (2016). Effects of action observation therapy on hand dexterity and EEG-based cortical activation patterns in patients with post-stroke hemiparesis. Topics in stroke rehabilitation, 23(5), 318-325.

Kuz, J. E., Van Heest, A. E., & House, J. H. (1999). Biceps-to-triceps transfer in tetraplegic patients: report of the medial routing technique and follow-up of three cases. *The Journal of hand surgery*, *24*(1), 161-172.

Lacey, S. H., Wilber, R. G., Peckham, P. H., & Freehafer, A. A. (1986). The posterior deltoid to triceps transfer: a clinical and biomechanical assessment. *The Journal of hand surgery*, *11*(4), 542-547.

Lamb, D. W., & Chan, K. M. (1983). Surgical reconstruction of the upper limb in traumatic tetraplegia. A review of 41 patients. *The Journal of bone and joint surgery. British volume*, *65*(3), 291-298.

Lance, J. W. (1980). Pathophysiology of spasticity and clinical experience with baclofen. *Spasticity: disordered motor control*, 185-204.

Lee, M. H. M., Liao, S. J., Kottke, F. J., & Lehmann, J. F. (1990). Acupuncture in physiatry. *Krusens Handbook of Physical Medicine and Rehabilitation, ed*, *4*, 402-32.

Lo, A. C., Guarino, P. D., Richards, L. G., Haselkorn, J. K., Wittenberg, G. F., Federman, D. G., ... & Bever Jr, C. T. (2010). Robot-assisted therapy for long-term upper-limb impairment after stroke. New England Journal of Medicine, 362(19), 1772-1783.

Lo, I. K. Y., Turner, R., Connolly, S., Delaney, G., & Roth, J. H. (1998). The outcome of tendon transfers for C6-spared quadriplegics. *Journal of Hand Surgery*, *23*(2), 156-161.

Lohse, K., Shirzad, N., Verster, A., Hodges, N., & Van der Loos, H. M. (2013). Video games and rehabilitation: using design principles to enhance engagement in physical therapy. *Journal of Neurologic Physical Therapy*, *37*(4), 166-175.

Mangold, S., Keller, T., Curt, A., & Dietz, V. (2005). Transcutaneous functional electrical stimulation for grasping in subjects with cervical spinal cord injury. *Spinal Cord*, *43*(1), 1.

Marino, R. J., Ditunno Jr, J. F., Donovan, W. H., & Maynard Jr, F. (1999). Neurologic recovery after traumatic spinal cord injury: data from the Model Spinal Cord Injury Systems. *Archives of physical medicine and rehabilitation*, *80*(11), 1391-1396.

Marino, R. J., Burns, S., Graves, D. E., Leiby, B. E., Kirshblum, S., & Lammertse, D. P. (2011). Upper-and lower-extremity motor recovery after traumatic cervical spinal cord injury: an update from the national spinal cord injury database. *Archives of physical medicine and rehabilitation*, *92*(3), 369-375.

Magill, R.A. (2001) Motor learning: concepts and applications. 6th Edn. New York, NY: McGrawHill.

McCarthy, C. K., House, J. H., Van Heest, A., Kawiecki, J. A., Dahl, A., & Hanson, D. (1997). Intrinsic balancing in reconstruction of the tetraplegic hand. *The Journal of hand surgery*, *22*(4), 596-604.

McSweeney, T. (1969) Discussion to Freehafer AA. Care of the hand in cervical spinal cord injuries. Paraplegia, 7:118-30.

Medina, J., Marcos-García, A., Jiménez, I., Muratore, G., & Méndez-Suárez, J. L. (2017). Biceps to Triceps Transfer in Tetraplegic Patients: Our Experience and Review of the Literature. *HAND, 12*(1), 85-90.

Medina, J., Marcos-García, A., Jiménez, I., Muratore, G., & Méndez-Suárez, J. L. (2017). Biceps to Triceps Transfer in Tetraplegic Patients: Our Experience and Review of the Literature. *HAND, 12*(1), 85-90.

Meiners, T., Abel, R., Lindel, K., & Mesecke, U. (2002). Improvements in activities of daily living following functional hand surgery for treatment of lesions to the cervical spinal cord: self-assessment by patients. *Spinal Cord*, *40*(11), 574.

Memberg, W. D., Crago, P. E., & Keith, M. W. (2003). Restoration of elbow extension via functional electrical stimulation in individuals with tetraplegia. *Journal of Rehabilitation Research & Development*, *40*(6).

Meythaler, J. M., Guin-Renfroe, S., Grabb, P., & Hadley, M. N. (1999). Long-term continuously infused intrathecal baclofen for spastic-dystonic hypertonia in traumatic brain injury: 1-year experience. *Archives of physical medicine and rehabilitation*, *80*(1), 13-19.

Midha, R. (2004). Nerve transfers for severe brachial plexus injuries: a review. *Neurosurgical focus*, *16*(5), 1-10.

Moberg, E. R. I. K. (1975). Surgical treatment for absent single-hand grip and elbow extension in quadriplegia. Principles and preliminary experience. *The Journal of bone and joint surgery. American volume*, *57*(2), 196-206.

Mohammed, K. D., Rothwell, A. G., Sinclair, S. W., Willems, S. M., & Bean, A. R. (1992). Upper-limb surgery for tetraplegia. *The Journal of bone and joint surgery. British volume*, *74*(6), 873-879.

Mohindra, M., Gogna, P., Sangwan, S. S., Gaba, S., & Kundu, Z. S. (2017). The scope of upper limb surgery for tetraplegics: Role of tendon transfers and Universal Cuff. *Acta orthopaedica et traumatologica turcica*, *51*(5), 367-371.

Mortimer, J. (1981) Motor Prostheses. Handbook of Physiology-The Nervous System II, American Physiological Society, 155-187.

Mulcahey, M. J., Lutz, C., Kozin, S. H., & Betz, R. R. (2003). Prospective evaluation of biceps to triceps and deltoid to triceps for elbow extension in tetraplegia. *The Journal of hand surgery*, *28*(6), 964-971.

Mulcahey, M. J., Betz, R. R., Kozin, S. H., Smith, B. T., Hutchinson, D., & Lutz, C. (2004). Implantation of the Freehand System® during initial rehabilitation using minimally invasive techniques. *Spinal Cord*, *42*(3), 146.

Mulcahey, M. J., Betz, R. R., Smith, B. T., Weiss, A. A., & Davis, S. E. (1997). Implanted functional electrical stimulation hand system in adolescents with spinal injuries: an evaluation. *Archives of physical medicine and rehabilitation*, *78*(6), 597-607.

Murphy, C. P., & Chuinard, R. G. (1988). Management of the upper extremity in traumatic tetraplegia. *Hand Clinics*, *4*(2), 201-209.

Nasser, M. E. T., Reda, M. A. E. H., Awad, M. R., Amin, I. R., & Assem, S. A. (2014). Effect of massed practice and somatosensory stimulation on the upper extremity function in patients with incomplete cervical spinal cord injury. *Alexandria Journal of Medicine*, *50*(2), 189-196.

Needham-Shropshire, B., Broton, J., Cameron, T., & Klose, J. (1997). Improved motor function in tetraplegics following neuromuscular stimulation-assisted arm ergometry. *The journal of spinal cord medicine*, *20*(1), 49-55.

Newell, K.M. (1991) Motor skill acquisition. Annu Rev Psychol, 42:213-37

Nightingale, T. E., Rouse, P. C., Walhin, J. P., Thompson, D., & Bilzon, J. L. (2018). Home-Based Exercise Enhances Health-Related Quality of Life in Persons With Spinal Cord Injury: A Randomized Controlled Trial. *Archives of physical medicine and rehabilitation*, *99*(10), 1998-2006.

Onose, G., Grozea, C., Anghelescu, A., Daia, C., Sinescu, C. J., Ciurea, A. V., ... & Popescu, C. (2012). On the feasibility of using motor imagery EEG-based brain–computer interface in chronic tetraplegics for assistive robotic arm control: a clinical test and long-term post-trial follow-up. *Spinal cord*, *50*(8), 599.

Osuagwu, B. C., Wallace, L., Fraser, M., & Vuckovic, A. (2016). Rehabilitation of hand in subacute tetraplegic patients based on brain computer interface and functional electrical stimulation: a randomised pilot study. *Journal of neural engineering*, *13*(6), 065002.

Overduin, S. A., d'Avella, A., Roh, J., & Bizzi, E. (2008). Modulation of muscle synergy recruitment in primate grasping. *Journal of Neuroscience*, *28*(4), 880-892.

Page, S. J., Szaflarski, J. P., Eliassen, J. C., Pan, H., & Cramer, S. C. (2009). Cortical plasticity following motor skill learning during mental practice in stroke. *Neurorehabilitation and neural repair*, *23*(4), 382-388.

Pandyan, A., Gregoric, M., Barnes, M. P., Wood, D., Wijck, F. V., Burridge, J., ... & Johnson, G. R. (2005). Spasticity: clinical perceptions, neurological realities and meaningful measurement. *Disability and rehabilitation*, *27*(1-2), 2-6.

Pannek, J., Pannek-Rademacher, S., & Wöllner, J. (2015). Use of complementary and alternative medicine in persons with spinal cord injury in Switzerland: a survey study. *Spinal cord*, *53*(7), 569.

Paralyzed Veterans of America Consortium for Spinal Cord Medicine. (1999). Outcomes following traumatic spinal cord injury: clinical practice guidelines for health care professionals. *The journal of spinal cord medicine.*

Paralyzed Veterans of America Consortium for Spinal Cord Medicine. (2005). Preservation of upper limb function following spinal cord injury: a clinical practice guideline for health-care professionals. *The journal of spinal cord medicine*, *28*(5), 434.

Paternostro-Sluga, T., Stieger, M. (2004) Hand splints in rehabilitation. Crit Rev Phys Rehabil Med, 16:233-256.

Patil, S., Raza, W. A., Jamil, F., Caley, R., & O'Connor, R. J. (2015). Functional electrical stimulation for the upper limb in tetraplegic spinal cord injury: a systematic review. *Journal of medical engineering & technology*, *39*(7), 419-423.

Peckham, P. H., Keith, M. W., Kilgore, K. L., Grill, J. H., Wuolle, K. S., Thrope, G. B., ... & Hentz, V. R. (2001). Efficacy of an implanted neuroprosthesis for restoring hand grasp in tetraplegia: a multicenter study. *Archives of physical medicine and rehabilitation*, *82*(10), 1380-1388.

Pedrocchi, A., Ferrante, S., Ambrosini, E., Gandolla, M., Casellato, C., Schauer, T., ... & Reichenfelser, W. (2013). MUNDUS project: MUltimodal Neuroprosthesis for daily Upper limb Support. *Journal of neuroengineering and rehabilitation*, *10*(1), 66.

Peng, T. H., Zhu, J. D., Chen, C. C., Tai, R. Y., Lee, C. Y., & Hsieh, Y. W. (2019). Action observation therapy for improving arm function, walking ability, and daily activity performance after stroke: a systematic review and meta-analysis. *Clinical rehabilitation*, 0269215519839108.

Peterchev, A. V., Wagner, T. A., Miranda, P. C., Nitsche, M. A., Paulus, W., Lisanby, S. H., ... & Bikson, M. (2012). Fundamentals of transcranial electric and magnetic stimulation dose: definition, selection, and reporting practices. Brain stimulation, 5(4), 435-453.

Peterson, C. L., Rogers, L. M., Bednar, M. S., Bryden, A. M., Keith, M. W., Perreault, E. J., & Murray, W. M. (2017). Posture-Dependent Corticomotor Excitability Differs Between the Transferred Biceps in Individuals With Tetraplegia and the Biceps of Nonimpaired Individuals. *Neurorehabilitation and neural repair*, *31*(4), 354-363.

Pfurtscheller, G., Linortner, P., Winkler, R., Korisek, G., & Müller-Putz, G. (2009). Discrimination of motor imagery-induced EEG patterns in patients with complete spinal cord injury. *Computational intelligence and neuroscience, 2009.*

Politis, M.J., Korchinski, M.A. (1990) Beneficial effects of acupuncture treatment following experimental spinal cord injury: a behavioral morphological and biochemical study. Acupunct Electrother Res, 15:37-49.

Popović, D., Stojanović, A., Pjanović, A., Radosavljević, S., Popović, M., Jović, S., & Vulović, D. (1999). Clinical evaluation of the bionic glove. *Archives of physical medicine and rehabilitation*, *80*(3), 299-304.

Popovic, M. R., Keller, T., Papas, I. P. I., Dietz, V., & Morari, M. (2001). Surface-stimulation technology for grasping and walking neuroprostheses. *IEEE Engineering in Medicine and Biology Magazine*, *20*(1), 82-93.

Popovic, M. R., Popovic, D. B., & Keller, T. (2002). Neuroprostheses for grasping. *Neurological research*, *24*(5), 443-452.

Popovic, M. R., Thrasher, T. A., Adams, M. E., Takes, V., Zivanovic, V., & Tonack, M. I. (2006). Functional electrical therapy: retraining grasping in spinal cord injury. *Spinal cord*, *44*(3), 143.

Portnova, A. A., Mukherjee, G., Peters, K. M., Yamane, A., & Steele, K. M. (2018). Design of a 3D-printed, open-source wrist-driven orthosis for individuals with spinal cord injury. *PloS one*, *13*(2), e0193106.

Potter-Baker, K. A., Janini, D. P., Lin, Y. L., Sankarasubramanian, V., Cunningham, D. A., Varnerin, N. M., ... & Plow, E. B. (2018). Transcranial direct current stimulation (tDCS) paired with massed practice training to promote adaptive plasticity and motor recovery in chronic incomplete tetraplegia: A pilot study. *The journal of spinal cord medicine*, *41*(5), 503-517.

Prasad, S., Aikat, R., Labani, S., & Khanna, N. (2018). Efficacy of Virtual Reality in Upper Limb Rehabilitation in Patients with Spinal Cord Injury: A Pilot Randomized Controlled Trial. *Asian spine journal*, *12*(5), 927.

Prochazka, A., Gauthier, M., Wieler, M., & Kenwell, Z. (1997). The bionic glove: an electrical stimulator garment that provides controlled grasp and hand opening in quadriplegia. *Archives of physical medicine and rehabilitation*, *78*(6), 608-614.

Rabischong, E., Benoit, P., Benichou, M., & Allieu, Y. (1993). Length–tension relationship of the posterior deltoid to triceps transfer in C6 tetraplegic patients. *Spinal Cord*, *31*(1), 33.

Raczka, R., Braun, R., & Waters, R. L. (1984). Posterior deltoid-to-triceps transfer in quadriplegia. *Clinical orthopaedics and related research*, (187), 163-167.

Ragnarsson, K. T. (2008). Functional electrical stimulation after spinal cord injury: current use, therapeutic effects and future directions. *Spinal cord*, *46*(4), 255.

Raineteau, O., & Schwab, M. E. (2001). Plasticity of motor systems after incomplete spinal cord injury. *Nature Reviews Neuroscience*, *2*(4), 263.

Ran, C., Ba, S., & Liu, X. (1992). Acupuncture treatment of spinal paraplegia with acupoints selected, basing on neuroanatomy. *World J Acupunct Mox*, *2*, 3-9.

Remy-Neris, O., Milcamps, J., Chikhi-Keromest, R., Thevenon, A., Bouttens, D., & Bouilland, S. (2003). Improved kinematics of unrestrained arm raising in C5–C6 tetraplegic subjects after deltoid-to-triceps transfer. *Spinal Cord*, *41*(8), 435.

Revol, M., Cormerais, A., Laffont, I., Pedelucq, J. P., Dizien, O., & Servant, J. M. (2002). Tendon transfers as applied to tetraplegia. *Hand clinics*, *18*(3), 423-439.

Rice, L. A., Smith, I., Kelleher, A. R., Greenwald, K., Hoelmer, C., & Boninger, M. L. (2013). Impact of the clinical practice guideline for preservation of upper limb function on transfer skills of persons with acute spinal cord injury. *Archives of physical medicine and rehabilitation*, *94*(7), 1230-1246.

Riemsma, R. P., Kirwan, J. R., Taal, E., & Rasker, H. J. J. (2009). Patient education for adults with rheumatoid arthritis. The Cochrane Database of Systematic Reviews.

Rieser, T. V., & Waters, R. L. (1986). Long-term follow-up of the Moberg key grip procedure. *The Journal of hand surgery*, *11*(5), 724-728.

Rivers, C. S., Fallah, N., Noonan, V. K., Whitehurst, D. G., Schwartz, C. E., Finkelstein, J. A., ... & Ho, C. (2018). Health conditions: effect on function, health-related quality of life, and life satisfaction after traumatic spinal cord injury. A prospective observational registry cohort study. *Archives of physical medicine and rehabilitation*, *99*(3), 443-451.

Robinson, M. A., Elliott, D., Hayes, S. J., Barton, G. J., & Bennett, S. J. (2014). Primary and submovement control of aiming in C6 tetraplegics following posterior deltoid transfer. *Journal of neuroengineering and rehabilitation*, *11*(1), 112.

Rothwell, A. G., Sinnott, K. A., Mohammed, K. D., Dunn, J. A., & Sinclair, S. W. (2003). Upper limb surgery for tetraplegia: a 10-year re-review of hand function. *The Journal of hand surgery*, *28*(3), 489-497.

Rushton, D. N. (2003). Functional electrical stimulation and rehabilitation—an hypothesis. *Medical engineering & physics*, *25*(1), 75-78.

Sabari, J.S. (2001). Teaching activities in occupational therapy. In: Pedretti LW, Early MB, eds. Occupational therapy: practice skill for physical dysfunction. 5th edn, 83-90.

Sale, P., Ceravolo, M. G., & Franceschini, M. (2014). Action observation therapy in the subacute phase promotes dexterity recovery in right-hemisphere stroke patients. BioMed research international, 2014.

Sandrow-Feinberg, H. R., Izzi, J., Shumsky, J. S., Zhukareva, V., & Houle, J. D. (2009). Forced exercise as a rehabilitation strategy after unilateral cervical spinal cord contusion injury. *Journal of neurotrauma*, *26*(5), 721-731.

Scandola, M., Tidoni, E., Avesani, R., Brunelli, G., Aglioti, S. M., & Moro, V. (2014). Rubber hand illusion induced by touching the face ipsilaterally to a deprived hand: evidence for plastic "somatotopic" remapping in tetraplegics. *Frontiers in Human Neuroscience*, *8*, 404.

Scandola, M., Aglioti, S. M., Pozeg, P., Avesani, R., & Moro, V. (2017). Motor imagery in spinal cord injured people is modulated by somatotopic coding, perspective taking, and post-lesional chronic pain. *Journal of neuropsychology*, *11*(3), 305-326.

Schmidt, R. A., Lee, T. D., Winstein, C., Wulf, G., & Zelaznik, H. N. (2018). *Motor control and learning: A behavioral emphasis*. Human kinetics.

Scott, T. R., & Vare, V. A. (2015). Sensitivity analysis of a novel five-degrees-of-freedom user command controller in people with spinal cord injury and non-injured for full upper extremity neuroprosthesis, wearable powered orthoses and prosthetics. *Medical & biological engineering & computing*, *53*(6), 511-523.

Seáñez-González, I., Pierella, C., Farshchiansadegh, A., Thorp, E., Wang, X., Parrish, T., & Mussa-Ivaldi, F. (2016). Body-machine interfaces after spinal cord injury: rehabilitation and brain plasticity. *Brain sciences*, *6*(4), 61.

Shaw, E. J., Stokes, T., Camosso-Stefinovic, J., Baker, R., Baker, G. A., & Jacoby, A. (2009). Self-management education for adults with epilepsy. The Cochrane Database of Systematic Reviews.

Shin, H. K., Cho, S. H., Jeon, H. S., Lee, Y. H., Song, J. C., Jang, S. H., ... & Kwon, Y. H. (2008). Cortical effect and functional recovery by the electromyography-triggered neuromuscular stimulation in chronic stroke patients. *Neuroscience letters*, *442*(3), 174-179.

Senjaya, F. & Midha, R. (2013). Nerve Transfer strategies for spinal cord injury. World Neurosurg, 80(6):319-26.

Sicuri, C., Porcellini, G., & Merolla, G. (2014). Robotics in shoulder rehabilitation. Muscles, ligaments and tendons journal, 4(2), 207.

Simcock, J. W., Dunn, J. A., Buckley, N. T., Mohammed, K. D., Beadel, G. P., & Rothwell, A. G. (2017). Identification of patients with cervical SCI suitable for early nerve transfer to achieve hand opening. *Spinal cord*, *55*(2), 131.

Sinnott, K. A., Dunn, J. A., Wangdell, J., Johanson, M. E., Hall, A. S., & Post, M. W. (2016). Measurement of outcomes of upper limb reconstructive surgery for tetraplegia. *Archives of physical medicine and rehabilitation*, *97*(6), S169-S181.

Sipski, M. L., & Richards, J. S. (2006). Spinal cord injury rehabilitation: state of the science. *American Journal of Physical Medicine & Rehabilitation*, *85*(4), 310-342.

Sriraman, A., Oishi, T., & Madhavan, S. (2014). Timing-dependent priming effects of tDCS on ankle motor skill learning. *Brain research*, *1581*, 23-29.

Smith, B. T., Betz, R. R., Mulcahey, M. J., & Triolo, R. J. (1994). Reliability of percutaneous intramuscular electrodes for upper extremity functional neuromuscular stimulation in adolescents with C5 tetraplegia. *Archives of physical medicine and rehabilitation*, *75*(9), 939-945.

Smith, B. T., Mulcahey, M. J., & Betz, R. R. (1996). Quantitative comparison of grasp and release abilities with and without functional neuromuscular stimulation in adolescents with tetraplegia. *Spinal Cord*, *34*(1), 16.

Snoek, G. J., IJzerman, M. J., Stoffers, T. S., & Zilvold, G. (2000). Use of the Ness-HandmasterTM to restore hand function in tetraplegia: clinical experiences in 10 patients. *Patient preferences for reconstructive interventions of the upper limb in tetraplegia*, *38*, 39.

Snoek, G. J., IJzerman, M. J., Hermens, H. J., Maxwell, D., & Biering-Sorensen, F. (2004). Survey of the needs of patients with spinal cord injury: impact and priority for improvement in hand function in tetraplegics. *Spinal cord*, *42*(9), 526.

Snoek, G. J., IJzerman, M. J., Post, M. W., Stiggelbout, A. M., Roach, M. J., & Zilvold, G. (2005). Choice-based evaluation for the improvement of upper-extremity function compared with other impairments in tetraplegia. *Archives of physical medicine and rehabilitation*, *86*(8), 1623-1630.

Squitieri, L., & Chung, K. C. (2008). Current utilization of reconstructive upper limb surgery in tetraplegia. *Hand Clinics*, *24*(2), 169-173.

Steeves, J. D. (2007). International Campaign for Cures of Spinal Cord Injury Paralysis. Guidelines for the conduct of clinical trials for spinal cord injury (SCI) as developed by the ICCP panel: clinical trial outcome measures. *Spinal Cord*, *45*, 206-221.

Sturma, A., Hruby, L. A., Prahm, C., Mayer, J. A., & Aszmann, O. C. (2018). Rehabilitation of upper extremity nerve injuries using surface EMG biofeedback: Protocols for clinical application. Frontiers in neuroscience, 12, 906.

Sun, L., Yin, D., Zhu, Y., Fan, M., Zang, L., Wu, Y., ... & Hu, Y. (2013). Cortical reorganization after motor imagery training in chronic stroke patients with severe motor impairment: a longitudinal fMRI study. *Neuroradiology*, *55*(7), 913-925.

Taylor, P., Esnouf, J., & Hobby, J. (2001). Pattern of use and user satisfaction of Neuro Control Freehand system. *Spinal Cord*, *39*(3), 156.

Taylor, P., Esnouf, J., & Hobby, J. (2002). The functional impact of the Freehand System on tetraplegic hand function. Clinical Results. *Spinal Cord*, *40*(11), 560.

Tazoe, T., & Perez, M. A. (2015). Effects of repetitive transcranial magnetic stimulation on recovery of function after spinal cord injury. *Archives of Physical Medicine and Rehabilitation*, *96*(4), S145-S155.

Teoli D, An J. Transcutaneous Electrical Nerve Stimulation (TENS) [Updated 2019 Jan 6]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2018 Jan-. Available from: https://www-ncbi-nlm-nih-gov.proxy1.lib.uwo.ca/books/NBK537188

Tigra, W., Navarro, B., Cherubini, A., Gorron, X., Gélis, A., Fattal, C., ... & Coste, C. A. (2016). A novel EMG interface for individuals with tetraplegia to pilot robot hand grasping. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *26*(2), 291-298

Thomas, C. K., Bakels, R., Klein, C. S., & Zijdewind, I. (2014). Human spinal cord injury: motor unit properties and behaviour. *Acta physiologica*, *210*(1), 5-19.

Tolmacheva, A., Savolainen, S., Kirveskari, E., Lioumis, P., Kuusela, L., Brandstack, N., ... & Shulga, A. (2017). Long-term paired associative stimulation enhances motor output of the tetraplegic hand. *Journal of neurotrauma*, *34*(18), 2668-2674.

Tomljanović, M., Spasić, M., Gabrilo, G., Uljević, O., & Foretić, N. (2011). Effects of five weeks of functional vs. traditional resistance training on anthropometric and motor performance variables. Kinesiology: International journal of fundamental and applied kinesiology, 43(2), 145- 154.

Triolo, R., Nathan, R., Handa, Y., Keith, M., Betz, R. R., Carroll, S., & Kantor, C. (1996). Challenges to clinical deployment of upper limb neuroprostheses. *Journal of rehabilitation research and development*, *33*, 111-122.

Trumbower, R. D., Hayes, H. B., Mitchell, G. S., Wolf, S. L., & Stahl, V. A. (2017). Effects of acute intermittent hypoxia on hand use after spinal cord trauma: a preliminary study. *Neurology*, *89*(18), 1904-1907.

Tsay, R.C. (1974). Textbook of Chinese acupuncture medicine: general introduction to acupuncture. Wappinger Falls, Association of Chinese Medicine and East-West Medical Centre,1:40-52.

Van Dijk, H., Jannink, M. J., & Hermens, H. J. (2005). Effect of augmented feedback on motor function of the affected upper extremity in rehabilitation patients: a systematic review of randomized controlled trials. *Journal of Rehabilitation Medicine*, *37*(4), 202-211.

van Dokkum, L. E. H., Ward, T., & Laffont, I. (2015). Brain computer interfaces for neurorehabilitation–its current status as a rehabilitation strategy post-stroke. Annals of physical and rehabilitation medicine, 58(1), 3-8.

Van Tuijl, J. H., Janssen-Potten, Y. J. M., & Seelen, H. A. M. (2002). Evaluation of upper extremity motor function tests in tetraplegics. *Spinal Cord*, *40*(2), 51.

van Wyk, K., Backwell, A., & Townson, A. (2015). A narrative literature review to direct spinal cord injury patient education programming. *Topics in spinal cord injury rehabilitation*, *21*(1), 49-60.

Vaynman, S., Ying, Z., & Gomez-Pinilla, F. (2003). Interplay between brain-derived neurotrophic factor and signal transduction modulators in the regulation of the effects of exercise on synaptic-plasticity. *Neuroscience*, *122*(3), 647-657.

Veldman, M. P., Zijdewind, I., Solnik, S., Maffiuletti, N. A., Berghuis, K. M. M., Javet, M., ... & Hortobágyi, T. (2015). Direct and crossed effects of somatosensory electrical stimulation on motor learning and neuronal plasticity in humans. *European journal of applied physiology*, *115*(12), 2505-2519.

Venugopalan, L., Taylor, P.N., Cobb, J.E., Swain, I.D. (2015). Upper limb functional electrical stimulation devices and their man-machine interfaces. Journal of Meical Egineering & Technology, 471-479.
Wagner, J. P., Curtin, C. M., Gater, D. R., & Chung, K. C. (2007). Perceptions of people with tetraplegia regarding surgery to improve upper-extremity function. *The Journal of hand surgery*, *32*(4), 483-490.

Wangdell, J., Carlsson, G., & Fridén, J. (2013). Enhanced independence: experiences after regaining grip function in people with tetraplegia. *Disability and rehabilitation*, *35*(23), 1968-1974.

Wangdell, J., Carlsson, G., & Friden, J. (2014). From regained function to daily use: experiences of surgical reconstruction of grip in people with tetraplegia. *Disability and rehabilitation*, *36*(8), 678-684.

Wangdell, J., & Fridén, J. (2018). Outcomes of reconstructive hand surgery in patients with tetraplegia and neuropathic pain. *Spinal cord*, *56*(12), 1194.

Ward, J. A., & Power, D. M. (2019). Restoring upper-limb function following cervical spinal cord injury: Current practice in the United Kingdom. *Journal of Musculoskeletal Surgery and Research*, *3*(1), 146.

Warsi, A., Wang, P. S., LaValley, M. P., Avorn, J., & Solomon, D. H. (2004). Self-management education programs in chronic disease: A systematic review and methodological critique of the literature. Archives of Internal Medicine, 164(15), 1641–1649.

Waters, R. L., Adkins, R. H., Yakura, J. S., & Sie, I. (1994). Motor and sensory recovery following incomplete tetraplegia. *Archives of physical medicine and rehabilitation*, *75*(3), 306-311.

Waters, R. L., Sie, I. H., Gellman, H., & Tognella, M. (1996). Functional hand surgery following tetraplegia. *Archives of physical medicine and rehabilitation*, *77*(1), 86-94.

Waters, R., Moore, K. R., Graboff, S. R., & Paris, K. (1985). Brachioradialis to flexor pollicis longus tendon transfer for active lateral pinch in the tetraplegic. *The Journal of hand surgery*, *10*(3), 385-391.

Welraeds, D., Ismail, A. A., & Parent, A. (2003). Functional reconstruction of the upper extremity in tetraplegia. Application of Moberg's and Allieu's procedures. *Acta Orthop Belg*, *69*(6), 537-545.

WHO. (2013). Spinal Cord Injury Fact Sheet N 384

Witt, P. L., & MacKinnon, J. (1986). Trager psychophysical integration: a method to improve chest mobility of patients with chronic lung disease. *Physical therapy*, *66*(2), 214-217.

Witiw, C.D. & Fehlings, M.G. (2015). Acute spinal cord injury. *Journal of Spinal Disorders and Techniques*, 202-210.

Winstein, C. J. (1991). Knowledge of results and motor learning—implications for physical therapy. *Physical therapy*, *71*(2), 140-149.

Wong, A. M., Leong, C. P., Su, T. Y., Yu, S. W., Tsai, W. C., & Chen, C. P. (2003). Clinical trial of acupuncture for patients with spinal cord injuries. *American journal of physical medicine & rehabilitation*, *82*(1), 21-27.

Wuolle, K. S., Van Doren, C. L., Bryden, A. M., Peckham, P. H., Keith, M. W., Kilgore, K. L., & Grill, J. H. (1999). Satisfaction with and usage of a hand neuroprosthesis. *Archives of physical medicine and rehabilitation*, *80*(2), 206-213.

Wuolle, K. S., Bryden, A. M., Peckham, P. H., Murray, P. K., & Keith, M. (2003). Satisfaction with upper-extremity surgery in individuals with tetraplegia. *Archives of physical medicine and rehabilitation*, *84*(8), 1145-1149.

Yeo, S. S., & Kwon, J. W. (2018). Wheelchair Skills Training for Functional Activity in Adults with Cervical Spinal Cord Injury. *International journal of sports medicine*, *39*(12), 924-928.

Ying, Z., Roy, R. R., Edgerton, V. R., & Gómez-Pinilla, F. (2005). Exercise restores levels of neurotrophins and synaptic plasticity following spinal cord injury. *Experimental neurology*, *193*(2), 411-419.

Yozbatiran, N., & Francisco, G. E. (2019). Robot-assisted Therapy for the Upper Limb after Cervical Spinal Cord Injury. *Physical Medicine and Rehabilitation Clinics*, *30*(2), 367-384.

Yue, Z., Zhang, X., & Wang, J. (2017). Hand rehabilitation robotics on poststroke motor recovery. Behavioural neurology, 2017.

Zancolli, E. (1975). Surgery for the Quadriplegic Hand With Active, Strong Wrist Extension Preserved A Study of 97 Cases. *Clinical Orthopaedics and Related Research®*, *112*, 101-113.

Zariffa, J., Steeves, J., & Pai, D. K. (2012). Changes in hand muscle synergies in subjects with spinal cord injury: characterization and functional implications. *The journal of spinal cord medicine*, *35*(5), 310-318.

Zhu, M. H., Wang, J., Gu, X. D., Shi, M. F., Zeng, M., Wang, C. Y., ... & Fu, J. M. (2015). Effect of action observation therapy on daily activities and motor recovery in stroke patients. *International Journal of Nursing Sciences*, *2*(3), 279-282.

Zoghi, M., & Galea, M. (2017). Brain Motor Control Assessment Post Early Intensive Hand Rehabilitation After Spinal Cord Injury. *Topics in spinal cord injury rehabilitation*, *24*(2), 157-166.

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 Capri Radialis Brevis
ECRL	Extensor Capri 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	Neuroprothesis
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

QIF	Quadriplegic Index Function
REL	Rehabilitation Engineering Laboratory Hand Function Test
ROM	Range of Motion
rTMS	Repetitive Transcranial Magnetic Stimulation
SCI	Spinal Cord Injury
SCIM	Spinal Cord Independence Measure
SEM	Standard Error of Mean
SRS	Stimulator Router System
SS	Somatosensory Peripheral Nerve Stimulation
VRS	Verbal Rating Scale
WUSPI	Wheelchair Users Shoulder Pain Index