Use and evaluation of assistive technologies for upper limb function in tetraplegia.

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Abstract

Context: More than half of all spinal cord injuries (SCI) occur at the cervical level leading to loss of upper limb function, restricted activity and reduced independence. Several technologies have been developed to assist with upper limb functions in the SCI population.

Objective: There is no clear clinical consensus on the effectiveness of the current assistive technologies for the cervical SCI population, hence this study reviews the literature in the years between 1999-2019.

Methods: A systematic review was performed on state-of-the-art assistive technology that supports and improves function of impaired upper limbs in cervical SCI populations. Combinations of terms covering assistive technology, SCI and upper limb were used in the search which resulted in a total of 1770 articles. Data extractions were performed on the selected studies which involved summarising details on the assistive technologies, characteristics of study participants, outcome measures, and improved upper limb functions when using the device.

Results: A total of 24 articles were found and grouped into five categories, including; neuroprostheses (invasive and non-invasive), orthotic devices, hybrid systems, robots, and arm supports. Only a few selected studies comprehensively reported characteristics of the participants. There was a wide range of outcome measures and all studies reported improvements in upper limb function with the devices.

Conclusions: This study highlighted that assistive technologies can improve functions of the upper limbs in SCI patients. It was challenging to draw generalisable conclusions because of factors such as heterogeneity of recruited participants, wide range of outcome measures and the different technologies employed.

Keywords: Assistive technology, tetraplegia, spinal cord injury, upper limb

Introduction

Each year in the UK 1,000 people sustain a traumatic spinal cord injury, and in total 40,000 people live with a spinal cord injury (SCI).[1–3] This number is higher in the United States, where approximately 294,000 (range 250,000 to 368,000) individuals live with SCI and each year around 17,810 new SCI cases are reported.[4–6] More than half of all cases of SCI occur at the cervical level leading to loss of hand and upper limb function.[6,7] This complex impairment results in restricted activity and independence, hence significantly compromising wellbeing and quality of life.[8,9] This life-changing injury remains a particular challenge to modern society as there is no cure. However, technological systems have been developed to restore some upper limb function for individuals with tetraplegia due to SCI including systems with neuroprostheses, orthotics, robots, and hybrid devices.

Individuals affected by high-level SCI see restoration of upper limb functions as a high priority.[10] Increased motor function in the hand and arms for this population can be achieved by surgical interventions or by assistive technologies.[11,12] Unlike therapeutic technologies, which seek to improve physical impairments, assistive technologies are designed to assist with the performance of specific tasks for the user and intended for use when neurological recovery has reached a plateau. There has been ongoing research and development on assistive technologies for tetraplegia in the last 20 years. There is no clear clinical consensus on the effectiveness of the current assistive technologies for the cervical SCI population; therefore, we decided to review the literature for the years between 1999-2019.

The aim of this study was to systematically review the state-of-the-art assistive technology that supports and improves function of impaired upper limbs in people with cervical SCI. In addition, clinical outcomes resulting from the implementation of such

technologies have been reviewed. To fulfil the aim of the study, we set out two main objectives and they were to:

(1) Describe the assistive technology, with a focus on devices that interface with the upper limbs; and
(2) Describe the outcome measures used when testing the efficacy of the technologies.

Methods

Search strategy

An electronic search of databases, including (CINAHL, AMED, EMBASE, PUBMED, MEDLINE, EMCARE) from 1999 to 2019 was performed. Initially, three categories essential to assess assistive technologies for clinical purposes were established: clinical condition, type of technology and affected body part. Combinations of search terms within the three categories were used, sometimes with truncation, to capture all possible variations (Table 1). Two examples of search strategies are shown in the supplementary materials (Example S1 and S2). In addition to the electronic search of the databases, the reference lists of relevant publications were checked.

Study selection

Initially, duplicate, low-level of evidence (for example articles with excluded terms) and irrelevant articles were discarded. Subsequently, the remaining articles were assessed based on their title and abstract, and 10% of these articles were blindly re-assessed by another reviewer. With the 10% of article re-assessment we found little difference of opinion, hence giving us confidence in the selected articles. Agreement was reached by discussion and reasoning in case of discrepancies. Following abstract and title screening, full-text of the

articles were reviewed for final screening.

Data extraction

The main categories for data extraction were type of assistive technology and its description, study participants, outlines of outcome measure, and functional ability with and without assistive technology. This information was used to summarise the efficacy of the current assistive technology for the upper limb in populations with tetraplegia.

Results

Study selection

The literature search in CINAHL, AMED, EMBASE, PUBMED, MEDLINE and EMCARE yielded 218, 71, 498, 483, 297 and 203 studies respectively. Following the initial study selection process, 371 studies were found. Subsequently, the abstracts of these studies were screened by searching for the predefined inclusion and exclusion terms (Table 1). Abstract screening yielded 37 studies. The 37 studies were further assessed for inclusion in the current study by reading the full-text of the articles while looking for contents relevant to assistive technologies for the upper limb in cervical SCI population, and a clear report on outcome measures. The full-text assessment resulted in selecting a total of 24 studies for the analysis in this paper (Figure 1). Of the 24 selected studies, 13 were identified as case studies or series,[13–25] two as clinical trials,[26,27] one as a clinical study,[28] and eight as cohort studies.[29–36]

Data extraction

Identified assistive technologies

In this study, assistive technologies for restoring upper limb function in populations with spinal cord injury were categorised into:

- Neuroprosthesis (invasive [20–26,29–34] and non-invasive [18,19,27,28]) is a system where muscles are stimulated by small electrical currents to generate motor functions;
- Orthosis is a non-invasive supportive device which assists with optimum use of remaining motor control[16,35,36];
- Hybrid system is a combination of multiple technologies such as neuroprosthesis and orthosis,[13,14] or powered orthosis;
- Robot is a non-invasive device generating functional movements without the need for users to have any residual motor control,[17] and;
- Antigravity arm support is an add-on device to other assistive technologies.[15]

From the literature search, 20 of the selected studies focused on neuroprostheses, with sixteen on invasive and four on non-invasive neuroprostheses. Selected studies focusing on assistive technologies other than neuroprostheses were limited, with three on orthotics, two on hybrid systems, one on robots, and one on antigravity arm supports. Descriptions of the identified assistive technologies are reported in Table 2.

Study participants

Characteristics of the participants recruited into each study are summarised in Table 3. Not all of the selected studies comprehensively reported characteristics of their participants, for example two studies did not report participants' sex,[14,28] two studies did not report participants' age,[16,31] and five studies did not report time between injury and participant recruitment.[14,20,28,31,34] In twenty-two studies, the neurological level of the injury ranged from C4-C8, and two were above C3. The time since injury varied widely (range from 3 months to 62 years) with no particular pattern or correlation to the assistive devices in the selected studies.

Outcome measures

The outcome measures adopted in the selected studies covered a variety of the domains that comprise the framework of International Classification of Functioning, Disability and Health (ICF).[37] In total, there were 30 different outcome measures assessing body functions and structures, activity, and participation domains (Supplementary Materials Table S1). In the body functions and structures domain, outcome measures described joint movement, force generation, active and passive range of motion (ROM) through a number of standardised tests, such as Jebsen-Taylor-Hand-Function (JTHF), and Toronto Rehabilitation Institute Hand Function Test (TRI-HFT). In the activity domain, outcome measures were evaluated using a range of tests including, Grasp-and-Release-Test (GRT), Activity of Daily Living (ADL), Action Research Arm Test (ARAT), Functional Independence Measure (FIM), and Spinal Cord Independence Measure (SCIM). In the participation domain, outcome measures assessed individuals when using the device in the community through tools and surveys, including the Craig Handicap Assessment and Reporting Tool (CHART). Only one study clearly reported on this domain, investigating social integration and occupation subscale,[30] and three studies carried out satisfaction surveys and participant questionnaires for using the device at home.[24,33,34]

Study functional outcomes

All studies reported improvement in functional ability of the upper limb while using the assistive devices (Supplementary Materials Table S1). Studies on neuroprostheses, both invasive and non-invasive devices, showed increased hand function, grip and pinch strength, average range of movement in the upper limb, and improvement in ADLs.

In one study, the application of non-invasive neuroprostheses showed an immediate increase in hand function in 63% of their compliant subjects of whom 15% scored a clinically

relevant change of 5.7 ARAT points.[28] Studies reported that grip strength was increased from 0.57N to 16.5N,[18] average range of movement in the forearm and wrist was increased by 9%,[27] and participants successfully performed at least three new ADL tasks.[18,19,27] Participants who continuously used the non-invasive neuroprosthesis devices showed a 75% higher performance of the ADL tasks.[27] Similarly, the effect of training with the device increased ARAT score by 2 points which is clinically important.[28] In addition, using non-invasive neuroprosthesis is thought to cause therapeutic effects and improve hand function.[28]

Participants with invasive neuroprostheses had undergone invasive methods to implant the device. The implanted components of the device consist of epimysial and intramuscular electrodes, electrode leads, and electromyography recording electrodes.[22,29,30] Some studies combined corrective surgeries such as tendon transfer with invasive neuroprostheses to further improve upper limb function.[24,30,32,33] Participants using invasive neuroprostheses were able to manipulate objects with varied size, surface and weights.[18,20,24,26,29,30,32,33] For example, GRT scores showed that 92% of participants improved the ability to manipulate objects,[29] participants at least doubled the number of objects manipulated or tasks performed,[30,32,33] and lateral and palmar grasp improved.[33] A study combining assistive technology with corrective surgeries such as arthrodesis, tendon transfers of muscles, and tendon synchronization, reported pinch force values at three stages (before intervention, after corrective surgery, and after surgery with assistive device).[30] Pinch force was increased from 4 N before to 12 N after corrective surgery and then to 19 N with device use, in other words pinch force increased by 58% after surgery with device use.[30] Increase in pinch force when using the device was also reported in lateral, palmar and finger grasps.[26,32] The range of lateral pinch force with the device was 11.6 N to17 N,[22,29,32,33] palmar pinch force was 6.5 N to 10.4 N,[29,32,33] and finger grasp was 14.7 N.[32] The improvement of grasp and release function and strength of grips contributed to the increased

success of the ADL tasks. ADL tasks reported in the selected studies varied widely, some studies allowed participants to choose the ADL tasks [24,30,32] and others predefined an extensive list of the tasks.[13,15,18,19,22,26,27,33,34] The results from ADL tests showed that participants experienced reduced disability and increased independence when using the invasive-neuroprosthesis.

Pinch force in participants increased with the use of an orthosis, such that in one study pinch force with an orthosis was 14.3 times greater than without the device.[36] Another study found that an orthosis increased maximum voluntary contraction (MVC), resulting in an increase of lateral grip force (the force ranging between 4.7 N to 22.3 N).[16] Only one study looked at the effect of an orthosis on performing ADL tasks, and reported that a greater number of tasks were achieved with the device compared to without.[16]

Studies on hybrid systems reported successful performance of GRT tasks,[13] and increased ability to manipulate objects using palmar grasp.[14]

The only study evaluating the antigravity arm support device on its own showed that the device facilitates ADL tasks such as eating.[15] A combination of mobile arm supports with other assistive devices such as neuroprostheses to support the weight of an arm has been reported but not evaluated on their own.[22]

Discussion

In this review, we defined a set of inclusion and exclusion criteria to systematically select original research articles focusing on state-of-the-art assistive technologies that support and improve function of impaired upper limbs in cervical SCI populations. The objectives of the paper are fulfilled by describing the assistive technologies and the outcome measures used to assess them.

During study selection, it was noted that a larger number of recent studies focused on developing control systems to regulate assistive technologies for the upper limbs.[38–47] Similarly, several studies reported the use of rehabilitation technologies as training and therapeutic tools to restore function in the upper limb.[48–59] These studies were excluded in this review paper so that a comprehensive focus could be made on the efficacy of assistive technologies that offer ongoing support to the upper limb for restoring function in people with cervical-level SCI. As a result of the study selection, the assistive technologies developed, trialled or used for restoring upper limb function were grouped into five categories, namely: neuroprostheses, orthoses, hybrid systems, robots, and antigravity arm supports. Some of the technologies described can be assigned to multiple categories. The Handmaster, for example, is a combination of a hand orthosis with surface electrodes and it is categorised under non-invasive neuroprosthesis.[18,19] One reason for placing the Handmaster in the non-invasive neuroprosthesis category is because the studies investigated the neuroprosthesis more than the orthotic part of the device. The same reasoning was used for other devices that spanned categories, such as antigravity arm support devices and neuroprosthesis.[15,22] However, devices with multiple technologies such as those reported in [13,14] are classified as hybrid systems. A survey study involving participants with SCI reported that many of the participants were not aware of the current assistive technologies, hence they were not aware of available options that could improve their independence and quality of life.[60] It is possible that the lack of clear and accessible categories of assistive technologies for restoring upper limb functions could have been a factor.

The incidences of SCIs vary across countries, regions and cities. A study reviewing global prevalence of SCI highlighted that the highest SCI prevalence was in the US (Alaska) whilst the lowest was in France (Rhone-Alpes region).[61] Globally, there was a greater percentage of males with SCI than females.[61] The demographics of recruited participants in

the selected studies showed a high male-to-female ratio, such as 11:1, 9:1, and 8:1,[31,32,36] and a wide age range between 19 to 54 years old. Others recruited either one participant or a relatively lower male-to-female ratio, such as a ratio below 5:1. In the UK, for the years between 1985 to 1988, male-to-female ratio for people sustaining a spinal cord injury, was 3.8:1 with an average age of 35.5 and 46 years old for males and females, respectively.[62] No more recent consensus about the epidemiology of SCI in the UK was found, however, the demographics of SCI patients in the developed countries is believed to have changed in terms of age more than sex over the last 20 to 40 years.[6,61,63,64] In the US, for the years between 1970 to 2015, the average age at injury increased from 29 to 43 years.[6] Similarly, in Scotland, for the years between 1994 and 2013, there was a notable increase of new SCI in the over 50 years old population and those with high level (C1-C4) tetraplegia.[63] With the exception of Japan, where SCI patients in their 70s are the largest age group,[65] a larger percentage of SCI patients are under the age of 30 in most countries.[61] The assistive technologies were population dependent and inclusion criteria for participant recruitment was focused more on injury level than age of participants or time since injury. Two of the selected papers recruited participants with C3 or higher levels of injury and the assistive technologies implemented were invasive neuroprostheses.[22,25] Participants in these two studies had limited to no voluntary contraction in the upper or lower limbs, hence it is possible that the decision on the type of device for this population was based on practicality for device operations. Similarly, participants in studies investigated orthotic devices for SCI had the ability to extend their wrist against gravity.[16,35,36] It would be beneficial for future studies to outline reasons behind opting to use an assistive device so that a library of different types of assistive devices and their suitability for different SCI populations can be established.

Prior to adopting an assistive device, SCI patients go through a rehabilitation process which commences in the acute care setting and lasts for 6 to 12 weeks, during this time the

focus is on patient's neurological stability status, indirect complications such as pressure ulcers, maintaining range of motion and preventing muscle atrophy.[66] Early rehabilitation is believed to prevent the development of joint contractures, especially contractures of elbow flexion and supination.[67] Therefore, identifying a suitable assistive technology to meet the needs of SCI patients at the early rehabilitation stage might improve the efficacy of the selected assistive device, hence enhance the patients' quality of life. The literature showed limited focus on the relationship between the efficacy of assistive technologies and time since injury. It was reported that assistive technologies built for functional purposes have therapeutic effects, however, small to no significant correlation was reported between time since injury and functional outcomes as a result of device use.[28] The selected literature assessed functional capabilities of the assistive devices through clinical outcome measures.

The outcome measures for assessing the assistive technologies were in the activity domain of the ICF. A limited number of the selected studies covered all three domains of the ICF; however, all covered the activity domain. All studies, except for three, followed the outcome measures identified by the Spinal Cord Injury Research Evidence (SCIRE) to assess the effect of device use on activities.[14,21,34] One of the three studies, investigating a hybrid system, assessed shoulder and scapular movements when using the device through the measurement of rotational speed, real-time angular variation and real-time force. Although these measurements indicated an increased palmar grasp, the study did not clearly report the translation of the measurements and their relevance to ICF activity domain.[14] Similarly, a study on invasive neuroprosthesis reported an improved volitional control across a continuous wrist angle but did not test the effect of this increased ability on participant's activities.[21] The third study, focused on elbow extension using invasive neuroprosthesis, developed new evaluations to assess the device because at the time the existing tests did not evaluate specific functions.[34] They reported that specific information (i.e. interval data) to

augment the muscle grade is needed because few gradations exist for a muscle that achieves full ROM and takes resistance. To obtain interval instead of ordinal data, they developed a technique of measuring the weight against gravity when participants were extending their elbows. Grip or pinch strength measurement was the most frequently used outcome measure after ADL tasks. Interestingly, this finding aligns with the choices professional practitioners make when selecting an outcome measure from SCIRE toolkit during their practice.[68] Professionals tend to choose the SCIM and FIM for assessing self-care and daily living, the GRT for assessing upper limb functions, and the Quebec user evaluation of satisfaction and predisposition assessment for assessing the effect of assistive technology. The outcome measures reported in this review included the FIM, SCIM, GRT and Graded Redefined Assessment of Strength, Sensibility, and Prehension (GRASSP) and these were reported to be reliable and valid.[69–71] Whereas the Quadriplegia Index of Function (QIF) is suggested for use only in non-ambulatory tetraplegia and its validity has not been investigated sufficiently.[69] It is important to note that, unlike the FIM, the SCIM, GRT, GRASSP and QIF were specifically designed for the SCI population. The FIM was designed to assess a broad range of disabling medical conditions, hence it might not specifically reflect on measures for SCI population. In addition, the selected papers in this review were limited by the lack of assessment on the efficacy of the assistive technologies during mobility. It is essential for future studies to assess assistive devices by looking at function, activity, and independence in the context of mobility from the ICF.

There are challenges and limitations that come with utilising assistive technologies for people with SCI. Loss of proprioception, for example, can make it challenging for people with SCI to adopt the aforementioned assistive technologies.[72] Other disadvantages of assistive technologies, such as invasive neuroprostheses, include risks associated with surgical operations and potentially additional surgeries to reposition migrated electrodes or

replace failed hardware components. However, compared to non-invasive neuroprostheses stronger forces and better muscle selectivity can be achieved with invasive neuroprostheses because the stimulation electrode can be implanted closer to the motor nerve and in deeper muscles.[73–75] In addition, the orthosis, robots, hybrid systems and antigravity arm supports are advantageous because of their non-invasive nature, however, they are disadvantages by the difficulties with donning, doffing and achieving selective muscle stimulation.[76] In addition to the generic disadvantages of these assistive devices, the technologies reported in the selected literature were limited, including the fabric-based soft robotic glove which could not generate adequate pinch grasp between the thumb and index finger due to a deficiency in their actuator design.[17] Furthermore, a study on grasp coordination with an invasive neuroprosthesis did not have an electrode to stimulate thenar muscle; therefore, they could not accurately measure the maximal palmar, lateral and tip-to-tip grip force.[20] It is worth mentioning that achieving upper limb movements with assistive devices alone can be challenging, therefore, a number of the studies reported a combination of surgical and technological interventions for improving upper limb functions.[24,30,32,33] For example, corrective surgeries such as tendon transfer were performed to augment the system.[32] A study reported that smaller objects such as pegs, and wooden blocks could be manipulated better with an active tenodesis grasp rather than with a transcutaneous functional electrical stimulation.[24] This is because the position of the object within the hand can be corrected more effectively and there is no time required for the interaction with the device. However, the electrical stimulation is advantageous and sometimes necessary to manipulate heavier or slippery objects. Assistive technologies combined with corrective surgeries could provide higher degrees of upper limb functionalities in tetraplegia.[33,73] Further research is needed to investigate the efficacy of assistive technologies when they are integrated with corrective surgeries such as tendon[77] or nerve transfer.[78]

In conclusion, here we categorised the assistive technologies into five main cohorts, hence making the evidence base of current technology more accessible and identifiable for clinicians, users, researchers and readers. There is evidence that the assistive technologies reported in this study can help people living with cervical SCI. Compared to the other technologies, a larger number of studies focused on the development of neuroprostheses two decades ago which was followed by much less interests in recent years. As a result, the application of neuroprostheses has been more extensively studied recently, hence future research is equipped to focus on developing user-control systems. There is an imbalance on how the efficacy of assistive technologies are assessed in relation to the three domains of the ICF. We recommend future studies on assistive technologies to follow the outcome measures identified by SCIRE and, when possible, equally address the three domains of the ICF in order to better quantify the effectiveness of assistive technologies. For example, future studies could focus on developing and following a methodology that would facilitate comparisons between different assistive devices.

Conflict of Interest

None.

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List of tables with captions

Table 1: Included and excluded terms used for electronically searching databases.

	Clinical Condition	**Type of Technology**	**Affected Body Part**
Search terms for inclusion	Spinal cord injury, SCI, spinal cord lesion, tetraplegia, quadriplegia, tetraplegic, quadriplegic, paralysis	Assistive technology, assistive device, orthotic device, splint, robotics, arm support, mobile arm support, anti-gravity support, neuroprostheses, functional electrical stimulation, FES, neuromuscular electrical stimulation, NMES, hybrid device, neuromuscular electrical stimulation, arm-weight bearing, implanted electrical stimulator, surface electrical stimulator, percutaneous electrical stimulator.	Upper limb, upper extremity, hand, arm, forearm, forelimb
Search terms for exclusion	Stroke, multiple sclerosis, MS, polio, poliomyelitis, paraplegic, paraplegia	Prosthesis, prosthetics, exoskeleton, passive assistive device, artificial limbs	Lower limb, lower extremity, leg

Table 2: Descriptive summary of assistive devices in the selected studies. Abbreviations: FES, Functional Electrical Stimulation; BCI, Brain-Computer Interface; IST-12, 12-channel implantable stimulator-telemeter; MES, Myoelectric Signals; EMG, Electromyographic.

Authors	Type of Assistive Device	Device description
Thorsen *et al.* [28]	Non-invasive neuroprosthesis	A one channel battery powered portable neuroprosthesis implementing myoelectric controlled functional electrical stimulation (MeCFES). Standard surface self-adhesive stimulation electrodes and EMG recording electrodes were used and connected to the MeCFES unit by flexible cables.
Alon and McBride [18]	Non-invasive neuroprosthesis	The Handmaster as described in Snoek et al. (2000). The control unit enables the user to choose between three exercise and three functional modes which are key grip and release, palmar grasp and release, and static open hand posture.
Snoek *et al.* [19]	Non-invasive neuroprosthesis	The Handmaster is a neuroprosthesis combining a spiral wrist and hand orthosis with integrated surface electrodes to activate muscles of the paralysed forearm and hand. Three exercise and two functional modes can be selected on the control unit. The functional modes provide, key grip and release, and palmar grasp and release, whilst exercise modes provide repetitive stimulation of the muscles.
Popovic *et al.* [27]	Non-invasive neuroprosthesis	The Bionic glove uses three channels of electrical stimulation to stimulate finger flexors, extensors, and thumb flexors. The control signal comes from a wrist position transducer mounted in the garment.
Bockbrader *et al.* [20]	Invasive neuroprosthesis	A BCI system comprising of a 96-channel Utah microelectrode array implanted in the left dominant cortex, which interfaces with transcutaneous forearm FES.
Kilgore *et al.* [29]	Invasive neuroprosthesis	IST-12 described in Kilgore et al. (2008).
Friedenberg *et al.* [21]	Invasive neuroprosthesis	A BCI system interfacing an Utah microelectrode array implanted in left primary motor cortex with FES technology. The FES system of a multi-channel stimulator flexible cuff consisting of up to 140 electrodes is wrapped around the subject's arm.
Memberg *et al.* [22]	Invasive neuroprosthesis	IST-12 described in Kilgore et al. (2008).
Gan *et al.* [23]	Invasive neuroprosthesis	Stimulus Router System (SRS) is a neuroprosthesis device in which only passive leads are implanted on branches of upper limb nerves and each lead picks up a portion of the current transmitted through the skin by an external stimulator. User triggers stimulation with small tooth-clicks that are detected by the wireless earpiece containing a 3-axis accelerometer. Wristlet stimulators are used to generate trains

		of pulses that are delivered through 4 electrode pads. Three of these pads are located over the 3 pick-up terminals and the fourth centred 12 cm proximal to the wrist crease on the posterior aspect of the forearm.
Kilgore *et al.* [30]	Invasive neuroprosthesis	IST-12, is a second-generation implantable neuroprosthesis to control hand grasp, forearm pronation and elbow extension. This device has the capacity to stimulate 12 paralysed muscles and record MES from two muscles under voluntary control. Device is controlled through implanted MES recording electrodes and MES processing circuitry. The system is driven from an external power and processing unit, which are connected to a coil that the participant places on the skin over the implanted device.
Mangold *et al.* [24]	Invasive neuroprosthesis	Neuroprosthesis comprising of transcutaneous self-adhesive electrodes which delivered FES via a stationary stimulation system and two portable systems (ETHZ- ParaCare FES system and Compex Motion). The control sensor varied between subjects from a digital push button switch, EMG signals and sliding potentiometer (analogue control).
Memberg *et al.* [31]	Invasive neuroprosthesis	An elbow extension neuroprosthesis previously reported by Bryden et al. (2000).
Taylor *et al.* [32]	Invasive neuroprosthesis	The Freehand system described in Carroll et al. (2000).
Peckham *et al.* [33]	Invasive neuroprosthesis	The Freehand system described in Carroll et al. (2000).
Yu *et al.* [25]	Invasive neuroprosthesis	A percutaneous intramuscular stimulator restoring elbow and shoulder functions without stimulating muscles of the hands. The device comprises of implanted electrodes in the shoulder and elbow muscles. The device is controlled via a switch on the headrest of the user's wheelchair and a position sensor on the contralateral shoulder. Weak stimulated shoulder movements were compensated for by adding a forearm orthosis.
Carroll *et al.* [26]	Invasive neuroprosthesis	The Freehand system, an implanted 8-channel neuroprosthesis device providing unilateral hand grasp and release. The device comprises of implanted and external components. The receiver-stimulator, epimysial electrodes, and inter-lead connectors are implanted internally whereas the external components are a controller, a transmitter, and a sensor at the shoulder. The neuroprosthesis is controlled using contralateral shoulder movements (either protraction-retraction or elevation-depression).

Bryden *et al.* [34]	Invasive neuroprosthesis	An elbow extension neuroprosthesis consisting of fully implanted triceps electrodes. This intervention is implemented as an addition to the Freehand System. Hand grasp was controlled using a shoulder or a wrist controller. Stimulation of the triceps for elbow extension was controlled using a switch or an accelerometer on the user's upper arm or applying a constant level of triceps stimulation when the hand grasp stimulation is active.
Portnova *et al.* [35]	Orthosis	A personalised three-dimensional printed wrist-driven orthosis comprising of 11 parts: hand, forearm, palmar and dorsal pieces, long and short bars, input link, thumb and finger pieces and two finger rings.
Kang *et al.* [36]	Orthosis	A personalised wrist-driven flexor hinge orthosis (WDFHO) consisting of a polyethylene forearm and a palmar cuff to grasp objects. The device stabilises the index and middle fingers along with the interphalangeal and metacarpophalangeal joints of the thumb. The device pushes together the thumb, index and middle fingers when the wrist is extended and releases the fingers when the wrist is flexed.
King *et al.* [16]	Orthosis	A lateral key grip orthosis comprising of a flexible cable running along the anterior surface of the forearm to the palmar region of the hand, further attaching to a ring around the thumb proximal phalanx. Tension on the cable pulls the thumb into palmar adduction so that a grip forms against the lateral region of the proximal or middle phalanx of the index finger.
Rohm *et al.* [13]	Hybrid System	A modular hybrid device consisting of a combination of FES with orthoses and BCI controller. The orthosis has anti-gravity module to support elbow flexion and extension during stimulation of triceps. The device comprised of a wrist-stabilising module to keep the wrist in neutral position enabling finger flexion. To facilitate the FES, a personalised neoprene sleeve with defined electrode positions was manufactured. The device was controlled using a motor imagery BCI and an analogue shoulder position sensor.
Varoto *et al.* [14]	Hybrid System	A hybrid device comprising of a glove that combines orthosis with forearm support along with neuromuscular electrical stimulation. While the elbow dynamic orthosis with forearm support allows elbow flexion and extension, static orthosis supports the wrist and neuromuscular electrical stimulation generates grasping function. The glove with force sensors also allows grasping force feedback via two user interface modes: visual by light emitting diodes or audio emitted by buzzer.
Cappello *et al.* [17]	Robots	A fabric-based soft robotic glove combined with modular, independent finger actuators attached by straps, hook and loop fasteners. Each actuator is comprised of three fabric layers and two air-tight bladders between each fabric pocket, one for flexion and the other for extension. The glove is controlled

		by a portable and self-contained control box with three buttons performing a finger flexion and extension, 3-point pinch and palmar grasp.
Asai and Kuroiwa [15]	Antigravity arm support (i.e. portable spring balancer (PSB), and mobile arm support (MAS))	Two devices reported: (1) A portable spring balancer - consisting of three metal parts: an aluminium tube containing a spring to assist the arm in resisting gravity; a proximal arm connected to the aluminium tube allowing vertical movement; and, a steel bar connecting the distal arm assembly to a distal cuff, supporting the arm at the elbow and wrist. (2) A mobile arm support consisting of a distal arm assembly, a proximal arm assembly, a trough, and a bracket. The device was mounted on the subject's wheelchair.

Table 3: Descriptive summary of study participants in the selected studies. Abbreviations: M, Male; F, Female; NR, Not Reported.

Authors	**Type of Assistive Device**	**Participant Number, Sex**	**Participant Age in Years* Range (Median)**	**Time Since Injury in Years** Range (Median)**	**Lesion at**
Thorsen *et al.* [28]	Non-invasive neuroprosthesis	27, NR	18-80 (NR)	NR	C5 - C7
Alon and McBride [18]	Non-invasive neuroprosthesis	7, M	25-46 (37)	3.1-17.3 (11.2)	C5 - C6
Snoek et a*l.* [19]	Non-invasive neuroprosthesis	10, M (8) and F (2)	20-65 (30.5)	0.5-6 (1)	C4 - C6
Popovic *et al.* [27]	Non-invasive neuroprosthesis	12, M	18-38 (22)	0.25-2 (2)	C5 - C7
Bockbrader *et al.* [20]	Invasive neuroprosthesis	1, M	27	NR	C5
Kilgore *et al.* [29]	Invasive neuroprosthesis	12, M (10) and F (2)	26-56 (37.8)	1-21 (3.8)	C5 - C6
Friedenberg *et al.* [21]	Invasive neuroprosthesis	1, M	27	6	C5 - C6
Memberg *et al.* [22]	Invasive neuroprosthesis	2, M and F	27 and 48	1.1 and 11	C1 - C3
Gan *et al.* [23]	Invasive neuroprosthesis	1, M	52	14	C6/C7
Kilgore *et al.* [30]	Invasive neuroprosthesis	3, NR	24-43 (34)	1-4 (2)	C5 - C7
Mangold *et al.* [24]	Invasive neuroprosthesis	11, M (9) and F (2)	15-70 (32)	1-62 (1)	C4 - C7
Memberg *et al.* [31]	Invasive neuroprosthesis	10, M (9) and F (1)	NR	NR	C5 - C6
Taylor *et al.* [32]	Invasive neuroprosthesis	9, M (8) and F (1)	NR (Mean = 38.4)	NR (Mean = 10.1)	C5 - C6
Peckham *et al.* [33]	Invasive neuroprosthesis	51, M (42) and F (9)	16-57 (32)	1.1-32.2 (4.6)	C5 - C6
Yu *et al.* [25]	Invasive neuroprosthesis	1, M	24	3	C3
Carroll *et al.* [26]	Invasive neuroprosthesis	6, M (4) and F (2)	21.9-36 (30.1)	1.2-11.3 (2.7)	C5 - C6
Bryden *et al.* [34]	Invasive neuroprosthesis	4, M	23-48 (33)	NR	C5 – C6
Portnova *et al.* [35]	Orthosis	3, M (2) and F (1)	40-65 (54)	16-28 (18.5)	C4 - C6
Kang *et al.* [36]	Orthosis	24, M (22) and F (2)	NR (37.1 ± 12.8) [+]	NR (5.6 ± 7.3) [+]	C6 - C7
King *et al.* [16]	Orthosis	7, M	NR	0.5-4 (0.5)	C5 - C7
Rohm *et al.* [13]	Hybrid System	1, M	41	1	C4

Varoto *et al.* [14]	Hybrid System	5, NR	29-42 (36)	NR	C5 - C8
Cappello *et al.* [17]	Robots	9, M (8) and F (1)	20-68 (53)	0.4-44 (33)	C4 - C7
Asai and Kuroiwa [15]	Antigravity arm support	4, M	15-50 (19)	1.2-0.3 (0.8)	C4 - C5

* Participant age range indicates the age of participant at the time of recruitment for the study.

** Time since injury indicates the time between injury and recruitment for the study.

[+] Mean ± SD

List of figures with captions

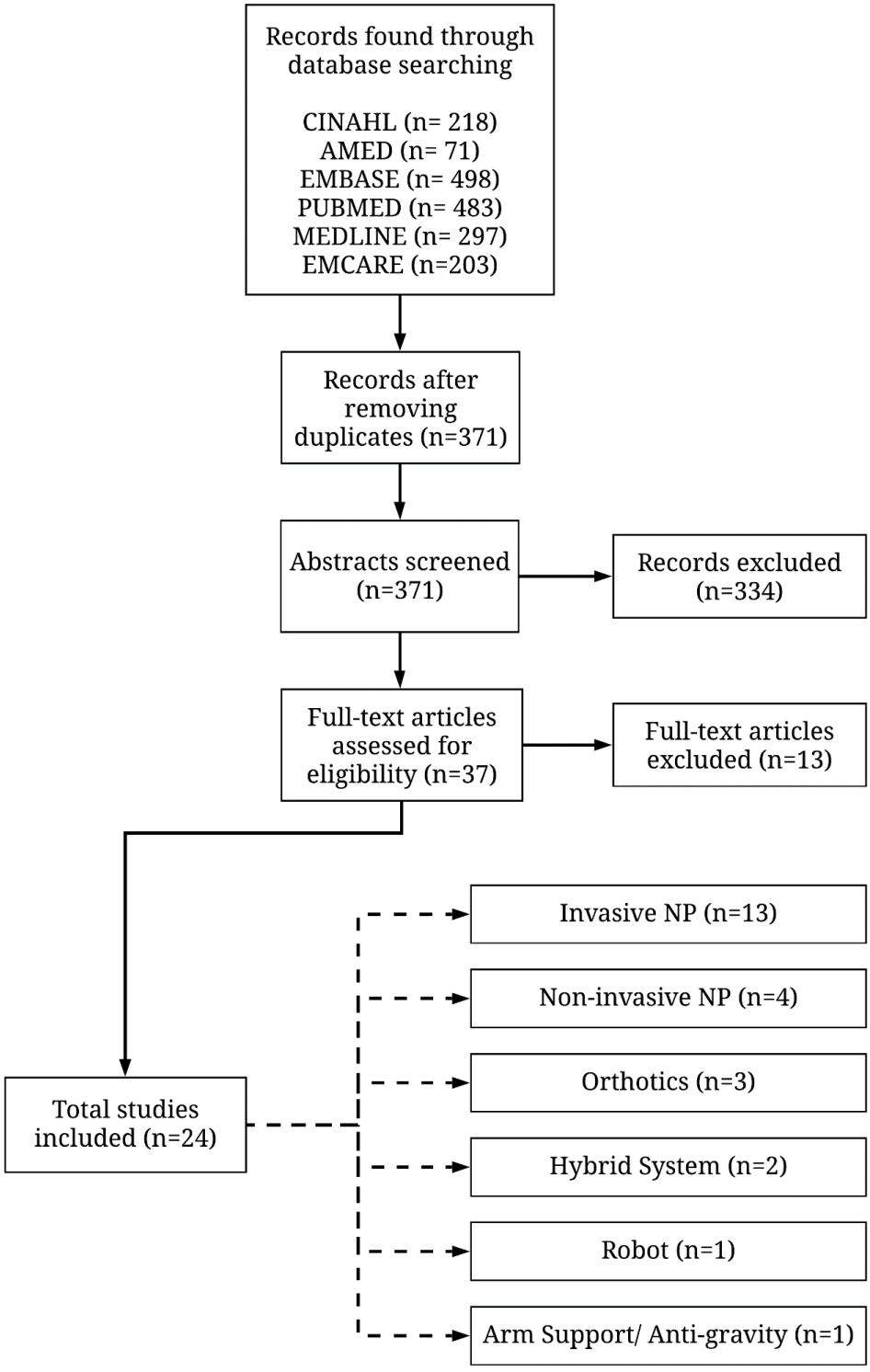

Figure 1: Study selection flow diagram for the searched databases. Abbreviations: NP, neuroprostheses.

Supplementary Materials

A. Search Strategy Examples for two databases

Example S1: Medline

Medline: (((exp "SELF-HELP DEVICES"/ OR exp "ORTHOTIC DEVICES"/ OR exp SPLINTS/ OR exp ROBOTICS/ OR exp "EXOSKELETON DEVICE"/ OR exp "ELECTRIC STIMULATION"/ OR exp "TRANSCUTANEOUS ELECTRIC NERVE STIMULATION"/ OR ("self-help device*" OR "self help device*" OR "assistive technology" OR "assistive device*" OR "orthotic device*" OR orthotic* OR splint* OR robotic* OR "arm support*" OR "anti-gravity support*" OR "antigravity support*").ti,ab OR (neuroprosthe* OR "functional electrical stimulat*" OR FES OR "neuromuscular electrical stimulat*" OR NMES OR "hybrid device*" OR "arm-weight bearing" OR "implanted electrical stimulat*" OR "surface electrical stimulat*" OR exoskeleton OR "percutaneous electrical stimulat*").ti,ab) AND (exp QUADRIPLEGIA/ OR (quadripleg* OR tetrapleg*).ti,ab)) AND (exp FORELIMB/ OR exp ARM/ OR exp "UPPER EXTREMITY"/ OR ("upper limb" OR "upper extremity" OR hand OR arm OR forearm OR forelimb OR brachium* OR antebrachium* OR "membrum superius").ti,ab)) [DT FROM 1999] [Languages English]"

Example S2: CINAHL

CINAHL: (((exp QUADRIPLEGIA/ OR (exp "SPINAL CORD INJURIES"/ AND exp "CERVICAL VERTEBRAE"/) OR (exp "CERVICAL CORD"/ AND (inur* OR lesion*).ti,ab) OR (quadripleg* OR tetrapleg* OR "cervical spinal cord injur*" OR "cervical spinal cord lesion*" OR (spinal cord lesion* AND cervical) OR (spinal cord injur* AND cervical)).ti,ab) AND (exp "UPPER EXTREMITY"/ OR exp ARM/ OR exp HAND/ OR exp FOREARM/ OR ("upper limb*" OR "upper extremit*" OR hand* OR arm* OR forearm* OR forelimb* OR brachium* OR antebrachium* OR "membrum superius").ti,ab)) AND (exp "ASSISTIVE TECHNOLOGY DEVICES"/ OR exp "ASSISTIVE TECHNOLOGY"/ OR exp ORTHOSES/ OR exp "EXOSKELETON DEVICES"/ OR exp SPLINTS/ OR exp ROBOTICS/ OR exp "ELECTRICAL STIMULATION, FUNCTIONAL"/ OR exp "ELECTRICAL STIMULATION, NEUROMUSCULAR"/ OR exp "TRANSCUTANEOUS ELECTRIC NERVE STIMULATION"/ OR ("self-help device*" OR "self help device*" OR "assistive technology" OR "assistive device*" OR "orthotic device*" OR orthotic* OR splint* OR robotic* OR "arm support*" OR "anti-gravity support*" OR "antigravity

support*").ti,ab OR (neuroprosthe* OR "functional electrical stimulat*" OR FES OR "neuromuscular electrical stimulat*" OR NMES OR "hybrid device*" OR "arm-weight bearing" OR "implanted electrical stimulat*" OR "surface electrical stimulat*" OR exoskeleton OR "percutaneous electrical stimulat*").ti,ab)) [DT FROM 1999] [Languages eng]"

B. Tables

Table S1: Overview of assistive devices in the selected studies, their corresponding outcome measures and participant's functional ability with and without using the device. Abbreviations: NP, Neuroprosthesis; GRT, Grasp and Release Test; JTHF, Jebsen Taylor Hand Function; MVC, Maximum Voluntary Contraction; TRI-HFT, Toronto Rehabilitation Institute Hand Function Test; MRC, Medical Research Council; CHART, Craig Handicap Assessment and Reporting Tool; QIF, Quadriplegia Index of Function; FIM, Functional Independence Measure; UEFT, Upper Extremity Function Test; GRASSP, Graded Redefined Assessment of Strength, Sensibility, and Prehension; ARAT, Action Research Arm Test; CUE-T, Capabilities of Upper Extremity Test; QIF-SF, Quadriplegia Index of Function-Short Form; SCIM-SR, Spinal Cord Independence Measure-Self-Report.
***Blue**: Non-invasive neuroprosthesis. **Green**: Invasive neuroprosthesis. **Yellow**: Orthosis. **White**: Hybrid system. **Grey**: Robot. **Purple**: Antigravity arm support.*

	Outcome Measure	Functional Ability without Assistive Device	Functional Ability with Assistive Device
Thorsen *et al.* (2013)	• ARAT • Proportions of subjects having positive change scores and the proportions exceeding the clinically relevant improvement.	• Wrist extension above grade 1 on the MRC scale.	• The immediate effect increasing hand function in 63% of the compliant participants and 15% of which exceeded the clinically relevant change of at least 5.7 ARAT points. Positive correlation of baseline ARAT with immediate effect was observed. • The intervention period using this device caused therapeutic effect and improved the hand function in 56% of the participants. • After training with the device, 67% of participants demonstrated an increase in the ARAT score by 2 points which was clinically important.
Alon & McBride (2003)	• Hand impairment tests: i. Grip strength. ii. Distance of finger motion from the distal palmar crease to the fingertip of the most extended finger iii. Fugl-Meyer hand subset of spherical grasp (scored 0=cannot perform, 1=ball kept in the hand against slight tug, and 2=ball is held against firm tug). • Three ADLs (pick up a telephone, eat food with a fork, perform 1 individually selected task, and 2 grasp, hold and release tasks).	• Adequate passive ROM of the fingers and thumb and a spasticity grade of less than 2. However, no grasp and release hand function and no finger motion. • The grip strength was 0.57 ± 0.98 N. • One out of seven was able to score 1 (hold the ball) without the device. • Results of the ADL showed 21% successful attempts.	• Significant improvements occurred in grip strength (16.5 ± 4.4 N), finger linear motion (8.4 ± 3.2cm), and Fugl-Meyer scores. • All participants successfully performed both the grasp, hold and release tasks, and were able to perform the task on the first attempt 92% of the time. • All participants successfully performed the three ADL tasks.
Snoek *et al.* (2000)	• Five ADLs (pouring water from a can, opening a jar, opening a bottle, taking a video tape out and putting it into a video player, one task selected by participant)	• Two participants lacked shoulder movement. • None of the participants could perform ADLs such as handling objects, pouring liquids, brushing, cutting, putting socks on, dry shaving.	• All participants were able to perform several tasks with the device. • Two participants were able to use the key as well as the palmar grasp mode for functional tasks, while the other two participants were only able to use the palmar grasp.

Popovic *et al.* (1999)	• Tonus of forearm and hand muscles using passive movement of fingers and flexible goniometers. • QIF • FIM • UEFT (11 tasks: combing hair, using a fork, picking up a VCR tape, picking up a full juice can, picking up a full pop/soda can, writing with a pen, answering the phone, brushing teeth, pouring from a 1 litre juice box, drinking from a mug, and handling finger food). • Weekly log forms.	• All participants had active wrist extension ranging from 10° to 45° and wrist extension strength 1+ to 5+ measured on a scale of 0 to 5. • Most of the participants lacked active extension and flexion of thumb and fingers, and flexion of the wrist. • Three participants had active wrist flexion to 40°. • One participant had active thumb extension and flexion to full range. • One participant had active finger flexion and extension to full range.	• Average range of movement increased from 2% to 11% when using the device. • The mean QIF increased by 49.5% (from 19.0 ± 6.5 to 28.4 ± 5.2). After 6 months of using the device only 36% of the maximum possible value was achieved. • The mean FIM value for all participants increased from 63.8 ± 10.4 to 79.0 ± 8.9 after 6 months. • 75% of ADL tasks were better performed in participants who continued using the device.
Bockbrader *et al.* (2019)	• Box and Block Test • GRASSP • ARAT • GRT • CUE-T • QIF-SF • SCIM-SR	• The participant had full strength during shoulder and elbow flexion, with limited wrist extension. • GRASSP strength was 24% of normal strength. • Prehension ability score based on ability to grip was 42% of normal. • Prehension performance was 30% of normal. • The total ARAT, grasp and grip were 32%, 44% and 33% of normal scores. • CUE-T total score was 45% of normal. • QIF-SF baseline score of the participant was 4. • SCIM-SR baseline score of the participant was 15.	• GRASSP strength improved to 80% of normal, achieving normal strength for five forearm muscle groups. • Prehension ability 92% of normal score. • Prehension performance improved to 50% of normal score due to better ability to pour a bottle, unscrew lids and perform 9-Hole peg. • Manual dexterity improved total ARAT (53% of normal), grasp (83% of normal) and grip (75% of normal) scores. • GRT success rate improved for all objects except for block. • Box and block test showed no improvements in transfer rates. • CUE-T total score improved to 82% of normal. However, no change was noted in reaching, lifting, pushing or pulling scores. • QIF-SF showed an increase in participant's expected level of independence for ADLs (QIF-SF scored 13). • SCIM-SR showed an increase in participant's level of independence (scored 24) for self-care and toileting and limited independence for bed mobility.
Kilgore *et al.* (2018)	• ROM • Grip strength • GRT	• No subject had any active moment in their fingers or thumb • Only one participant could manipulate as many as four out of six objects.	• Stimulation produced active extension and flexion for all five digits in all participants, with total ROM between 105° to 41°. • There was a significant difference in grasp strength for both lateral (~17 N post-implant with device) and palmar (~6.5 N post-implant with device) grasps. • All participants manipulated the same number of objects. In addition, three participants manipulated one extra object and one of the participants manipulated two extra objects.

Friedenberg *et al.* (2017)	• Neural activity measured by mean wavelet power • Cue angles measured on a protractor	• Complete paralysis of hand and wrist.	• Participant successfully hit the target angles in the set of three training blocks at a rate of 90.3 ± 3.5% (mean ± standard error), where success was defined as maintaining position within a ±15° window around the target cue angle for at least two continuous seconds. • Participant was able to volitionally control own graded muscle contraction across a continuous range of angles. The participant achieved an accuracy of 89.6 ± 4.4% including successes on 14 out of 18 cues for angles that had not been attempted previously. • Participant sustained flexion of paralysed wrist and hand, and reliable pointing at the target angles with an average success rate of 88.9 ± 3.7%.
Memberg *et al.* (2014)	• ROM (wrist, forearm, elbow, and shoulder) • Grip strength • Joint moments • Six ADLs (eating with a fork and finger food, hand shaking, nose scratching, nose wiping with a tissue, face washing, and teeth brushing).	• Participants had complete motor paralysis in at least one upper extremity. • Neither subjects were able to support the weight of their arm with stimulation of their shoulder muscles alone.	• Shoulder abduction moments evoked by suprascapular and axillary nerve stimulation showed large increase. Stimulation of the musculocutaneous nerve activated the biceps and brachialis, producing elbow flexion. Radial nerve stimulation activated two muscles at the elbow: triceps causing extension, and brachioradialis causing flexion. The elbow flexion and extension moments were sufficient for moving the arm to perform ADL. • Stimulated lateral pinch strength ranged from 11.6 to 25.5 N in the two subjects. • ROM at the shoulder: flexion ranged from 47° to 74°, adduction ranged from 3° to 8°, abduction ranged from 25° to 27°, internal rotation was 64°. • ROM at the elbow: extension 0°, flexion ranged from 88° to 109°. • ROM at the forearm: pronation ranged from 0° to 15°, supination ranged from 18° to 57°. • ROM at the wrist: extension was -10°, flexion was 18°. • ADLs: o Feeding with a fork - success depended on spasticity level on the day; o Eating finger foods - successful with some help; scratching nose - successful; o Wiping nose with tissue - success with some help; o Washing face with washcloth - somewhat successful with help; o Brushing teeth - somewhat successful with help; and o Shaking hands - successful.
Gan *et al.* (2012)	• Maximal grip strength • Thumb-finger aperture (hand-opening measurement)	• Unable to generate a measurable grip force on the dynamometer. • Voluntary flexion at the wrist achieved an aperture of hand opening of 4 cm between the tips of the forefinger and thumb. • A maximal grip force of 29.6 N was achieved with a 30/s train of pulses (300ms, 19mA) applied to the flexors.	• Mean maximal grip force ranged from 50 to 100 N in 100 days post-implant. • 14 cm thumb-finger separation was achieved during maximal stimulation after 4 months which was 4cm greater than the separation achieved with surface FES prior to surgery.

Kilgore *et al.* (2008)	• Body functions and structures:
	  ○ Grasp
	  ○ pinch force
	• Activities:
	  ○ GRT
	  ○ ADLs (feeding, grooming, writing and other activities specified by participant)
	• Participation:
	  ○ CHART
		• Pinch force was ranging from 2 to 11 N for all three participants.
		• Grasp release test performance showed that two out of three participants were able to complete peg, block and can tasks.
		• Participants were unable to perform activities they were set out to do with the NP device.
			• All participants improved their pinch force strength such that one participant demonstrated an increase in pinch force from 4 N before surgery, to 12 N after tendon transfer surgery (without device use) and then to 19 N (with device use).
			• All participants were able to double the number of objects manipulated in the grasp and release test. Two out of three participants were able to complete all six tasks for this test.
			• All participants improved in at least five activities with all demonstrating improvement in eating with a fork, drinking from a glass, and writing. Two of the three participants improved performance in 5 out of 11 tasks and one participant improved performance in 9 out of 11 tasks.
			• All participants demonstrated increased scores for the physical independence subscale. No changes in social integration were noticed in two of the participants and one participant increased their social integration subscale. One participant showed improvement in mobility subscale whereas the other two showed a slight decrease in this subscale. Two of the participants reported a decrease in the occupation subscale and one reported no change.

Mangold *et al.* (2005)	• Sollerman test (11 tasks, including manipulating objects of different sizes, geometries, and complexities). • Self-designed ADL functional test focusing on grasp-and-release tasks. • Status of muscle strength • Follow up query assessing the applicability of device in hospital and at home.	• No active palmar or lateral grasp functions. • Sufficient proximal arm function.	• Two participants showed improvements in muscle strength and facilitation of active movement with the device. • Eight participants demonstrated improved grasp function and performance in ADLs. • Most improvement in grasp function was observed in those participants who were not able to grasp bimanually or had no tenodesis grasp. • All participants (11 in total) used the device during their training programme. Number of participants used the device for ADL in rehabilitation centre and at home reduced to four and two.

Memberg *et al.* (2003)	• Strength measurement: moments generated by elbow flexion at 30°, 60°, 90°, and 120° while shoulder was positioned at 90° abduction and 0° horizontal adduction (keeping the upper arm horizontal, and the elbow in line with both acromia). • Workspace Assessment: assessing the effect of triceps on the controllable workspace by having participants reach, grasp, and move a book-like object from high location or orientation to a low location or orientation. Success rates and acquisition times were recorded.	• Only one participant was able to extend their arms against gravity without stimulation, using self-triggering spasm that resulted in triceps activation.	• Average stimulated elbow extension moments for the 11 arms with the elbow at 90° flexion ranged from 0.8 to 13.3 Nm. • 8 of the 11 arms were able to extend against gravity with triceps stimulation. • The elbow moment generated by triceps stimulation at 90° and 120° elbow flexion was significantly greater than the elbow moment produced by the posterior deltoid tendon transfer. • Elbow extension moment by participants with posterior deltoid tendon transfer ranged from 0 to 11.2 Nm. However, no difference in elbow moment between the two elbow extension methods at 30° elbow flexion. • The quantitative workspace assessment was more successful with stimulation than without. Success rate varied from 15-61% and it was improved for all participant at both far and near locations, similarly for when the book oriented vertically. • Average acquisition times with triceps stimulation were less than without the stimulation for 4 out of 5 arms, such that improvement in average acquisition time ranged from 3.2 to 6.4s.
Taylor *et al.* (2002)	• GRT (wooden pegs, a 250 g weight, a plunger, wooden cubes, a plastic cylinder, a small juice can, a videotape). • Grip strength • Eight ADL tasks chosen by participant.	• Participants with C5 injury were unable to complete any GRT tasks. • Participants with C6 injury were able to complete some of the tasks involving light objects or small force. • Four of the participants had sufficient tenodesis grip with a mean lateral, palmar and five finger grasps of 0.93 N, 0.96 N, and 1.04 N, respectively.	• GRT score was improved when device was used, and participants performed on average 5.1 types of task (maximum 6). • The mean lateral, palmar and five finger grasps had increased to 15.2 N, 10.4 N and 14.7 N respectively at 1-year post training. • Most of the selected tasks were achieved in the ADL assessment indicating a significant improvement in independence.
Peckham *et al.* (2001)	• Pinch strength • Active ROM • GRT • ADL Abilities, and ADL assessment tests • Satisfaction survey	• Lateral and palmar pinch forces were 0.3 N and 0 N, respectively. • Participants were able to manipulate smaller and lighter objects. • 68% of the participants were able to demonstrate lateral grasp using a peg, whereas none of the participants could successfully manipulate a weight or a fork. • 57%, 16%, and 7% of the participants were able to demonstrate palmer grasp using a block, a can and a tape, respectively.	• Lateral and palmar pinch forces were increased to 12 N and 6.6 N, respectively • 98% of participant moved at least 1 more object with the neuroprosthesis and 37% improved by moving at least 3 more objects. • 100%, 90% and 86% of the participants demonstrated lateral grasp by manipulating a peg, a weight, a fork respectively. • 98%, 78%, 72% of the participants demonstrated palmar grasp by manipulating a block, a can and a tape, respectively. • Disability was reduced in all assessed participants as measured by either ADL Abilities or ADL Assessment Tests. • All assessed participants improved in independence in at least 1 task and 64% in at least 3 tasks. • Satisfaction survey showed that 97% of participants will recommend the device to others, and 91% state that the device improved their quality of life.

Yu *et al.* (2001)	• Stimulated active ROM (SAROM) • Self-feeding activities	• Fair voluntary shoulder elevation and retraction bilaterally. No other voluntary muscle contraction in the upper limbs.	• SAROM against gravity included 60° of shoulder abduction, 45° of shoulder flexion, 10° of shoulder external rotation with the shoulder passively abducted to 90°, and 110° of elbow flexion. • Stimulated elbow extension lacked 20° of full extension with gravity eliminated. • Subject was able to pick up mashed potatoes from a plate and bring them to his mouth.
Carroll *et al.* (2000)	• Pinch forces • GRT (peg, weight, fork, can, block and tape) • Eight ADLs (including using a telephone, drinking from a cup, brushing teeth and writing with a pen)	• No voluntary finger or thumb movements • Minimal or no wrist extension • Only light items (peg and block) could be manipulated due to passive tenodesis.	• Pinch forces, lateral and palmar show a substantial increase in force with the device. • All subjects were able to grasp, move and release more objects within the test period with the neuroprosthesis than without it. • Tenodesis function appeared to be improved in four subjects after implantation of the device. • During ADL tasks, participants required less assistance 73% of the time. • Improvements in hand function were seen in 97% of activities.
Bryden *et al.* (2000)	• ROM • Five ADLs (activating a slide dimmer light switch, activating an overhead pull-chain light switch, hanging a garment, using a wall-mounted paper towel dispenser, and acquiring and placing an object on a shelf). • A participant survey for home use of the device.	• All participants had passive elbow extension that was within normal limit. • No participant could attain full elbow extension against gravity. • Active elbow extension was either absent or less than full range without stimulated triceps for all participants even for those with the posterior deltoid to triceps transfer.	• All participants attained full elbow extension (i.e. to zero degrees). • All were able to abduct their shoulder by at least 29° while maintaining full elbow extension with triceps stimulation on versus off. • All participants reached their max shoulder abduction (i.e. to their passive limits) while maintaining full elbow extension. • All participants were able to extend the elbow against gravity repetitively without added weight, with the number of repetitions ranged from 12-43. All participants could resist at least 0.5 kg and one could resist almost 3.5 kg against gravity. • All participants showed improved functional performance in 92% of tasks. • Use of stimulated elbow extension reduced the amount of assistance that was required by 56%. • All participants required less assistance with stimulated triceps to perform at least one task. • Three of four participants (4 extremities) preferred to perform 100% of the tasks with stimulated elbow extension. • All found at least some of the tasks easier to perform with stimulated elbow extension. • Participants showed regular use of the device at their home and community.

Portnova *et al.* (2018)	• Box-and-Blocks test • JTHF test • Three-point pinch force	• All participants had little to no mobility in their fingers but were able to extend their wrists against gravity.	• Two out of three participants showed improvement during the Box-and-Block test and they managed to transfer more blocks under one minute. • There was a large variation in participants' abilities during JTHF test. One participant took shorter time to complete the small object task while another took longer for the same task while both using the orthosis. • Pinch force test showed that two out of three individuals increased the strength of their three-jaw chuck grasp and the key grip was more natural.
Kang *et al.* (2013)	• Three-point pinch force • MVC of wrist extension	• Average pinch force for all participant was 0.64 ± 0.42 N. • The manual muscle test (MMT) was scored at least grade 3 for all subjects. • Wrist extension muscle voluntary contraction ranged from 1.92 Nm at 29.4° to 0.46 Nm at 26.4°.	• Pinch force was 7.26 ± 3.48 N which is 14.3 times greater than pinch force without the orthosis. • Greater MVC was recorded which resulted in a greater pinch force.
King *et al.* (2009)	• Preston pinch meter • Thirteen ADLs (remote control, card in and out, fork and putty, key in and out, key Turn, horizontal zip open and close, vertical zip open and close, and electric plug in and out)	• Wrist extension strength was greater than grade 3 and thumb flexion was less than grade 3. • Lateral key grip force without orthosis was 4.3 N (range 2.0–8.0 N). • Limited ADL tasks.	• Participants increased lateral key grip force and achieved an average force of 13.1 N (range 4.7– 22.3 N). • Greater number of ADL tasks achieved with orthosis.
Rohm *et al.* (2013)	• FES-generated GRT • Three ADLs (pick up a pretzel stick to eat, writing task, eating an ice cream cone)	• Shoulder: Active abduction, extension and flexion up to 30°. All grade 3/5. Full passive ROM. • Elbow: No active flexion (biceps grade 0/5, brachioradial muscle grade 0/5), no active extension (triceps grade 0/5). Full passive ROM. • Forearm: no active supination (grade0/5). No active pronation (grade 0/5). Full passive ROM. • Wrist, thumb and fingers: No active movements (grade 0/5). Almost full passive ROM in finger joints, full wrist and thumb ROM.	• Ability to successfully perform GRT tasks. Within trails of one minute, the participant succeeded transferring Double blocks (7 completions out of 7 attempts) and Pegs (10 completion out of 18 attempts) over the frame of a box.

Varoto *et al.* (2008)	• Rotation speed • Real-time angular variation • Real-time force measurement	• Shoulder: Active movements of the shoulder and scapula. • Wrist, thumb and fingers: Limited active grasping functions.	• Combining shoulder and scapula movements with the increased ability to manipulate objects using palmar grasp.
Cappello *et al.* (2018)	• TRI-HFT to identify ability to manipulate objects and weights that would be encountered during ADL. This test is divided into three parts: i. Ten ADLs to manipulate objects using palmar and pinch grasps. ii. Strength test – qualitative test using weighted objects. iii. Strength test – quantitative test using a hand-held dynamometer.	• Limited hand function, specifically strength and range of motion. • TRI-HFT average performance of 53.88 ± 24.20% was recorded. • Average lift force of 1.76 ± 4.32 N was recorded.	• Average score of 87.30 ± 11.82% on TRI-HFT. • The device provided a very firm and reliable palmar grasp, however improvement in pinch force was limited. • Mean lift force improved across all participants and a mean force of 2.76 ± 5.18 N was achieved.
Asai & Kuroiwa (1999)	• One ADL (consumption of yogurt over a period with a tablespoon).	• Inability of participants to perform a predefined ADL (namely eating yoghurt) independently.	• Three out of four of the participants consumed yogurt more easily with both (portable spring balancer (PSB) and mobile arm support (MAS)) devices. • All participants, except for one, showed larger mean consumption with PSB than MAS. The mean scores for one participant was inconsistent as it was initially reported not different between the two orthosis, but after repeating the tests the consumption using MAS almost doubled compared to using PBS. • Gradual improvement in task performance was noted as subjects demonstrated a positive uniform trend in both phases of using the PSB and MAS