Current Trends in the Management of the Upper Limb in Spinal Cord Injury

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Abstract There are nearly 12,000 new cases of spinal cord injury each year. About half of those involve some part of the arm and hand, representing significant disability and dependence for those patients. Restoration of upper limb function remains a high priority in rehabilitation; however, treatment protocols are widely variable and poorly defined. Recent research efforts fall into three main categories: therapeutic interventions, surgical reconstruction, and robotic developments. Therapeutic interventions involving high repetitions of motor and sensory input are under investigation but have limited support in the literature. Patients with incomplete injuries have a better prognosis. Surgical reconstruction techniques are evolving from advances in treatment of brachial plexopathy. Although these hold great potential for return of function, they are also high-risk techniques for which complications and inconsistent results have been reported. Finally, robotic developments, including exoskeletons and implants, show great promise but still have practical constraints. Management of the upper limb remains a complicated problem and more research efforts should be devoted to defining strategies for intervention.

Keywords Upper limb · Tetraplegia · Spinal cord injury · Rehabilitation · Activity-based therapy · Surgical reconstruction · Robotics

Introduction

There are approximately 12,000 new spinal cord injuries (SCIs) per year [1]. Of these, 50 % are reported to be cervical [1], representing at least some impairment of the arm and hand, with C5 being the commonest injury level [2]. Skilled arm and hand function is essential to daily interactions with the environment, dictates patients' independence, and gives meaning to life. Recovery of these functions is consistently rated as a high priority for patients with tetraplegia [3, 4]. Thus, it appears that a great potential for improving the quality of life of these individuals lies within rehabilitation and restoration of the upper limb function. With advancements in medical care for individuals with SCI, we have seen an increase in their life expectancy, desire to restore function, and desire to live productive, meaningful lives.

Despite this, very little research effort is directed at understanding and optimizing interventions for the upper extremity (UE). The complexity of the hand, paired with the many degrees of freedom at the shoulder, make the UE a more complicated “fix” than the lower extremity (LE). Although most researchers agree that high repetition and patterned activity are important for motor recovery and cortical reorganization, the pattern is not simple to define, like walking [5–8].

Owing to the complexity of rehabilitation and restoration of the UE following a cervical SCI, it is difficult to attain high levels of activity and maintain typical kinematics [5]. To further complicate the UE rehabilitation process after paralysis, there is no standard protocol of interventions in the therapeutic or surgical arenas. Functional electrical stimulation is one therapeutic intervention being used to perform a specific movement pattern and complete functional tasks that would otherwise be unobtainable [7, 9, 10]. Research has shown that combining task-specific training with electrical

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stimulation yields better results in terms of neurological and functional improvements than either of them alone [11]. But several factors may impact an individual's response to stimulation and its effective use, including long-term muscle atrophy and lower motor neuron damage [12]. A second intervention gaining popularity is gravity-compensation training (GCT), using mobile arm supports, exoskeletons, and or robotics. GCT promotes strengthening within a patient's available range of motion by reducing the effects of gravity and allowing near normal kinematics and increased active motion and endurance throughout the UE. However, there is little published research regarding GCT and its application in patients with SCI, although the effects of GCT are well documented in those individuals with stroke, demyelinating disease, and brain injury [13–16]. Another option gaining popularity is surgical repair and restoration done through techniques such as nerve and tendon transfers. Much of the literature surrounding surgical interventions for those with SCI has been modeled off surgical intervention for those with brachial plexus injuries, but its use in the SCI population is still relatively less studied.

The goal of this article is to highlight advances in UE research in the SCI population over the last year.

Methods

A search was conducted in the PubMed and Cinhal databases for “upper extremity and SCI,” limited to articles with publication dates from January 2012 to May 2013. Only English language articles where UE intervention was the primary purpose of the report were included in the review. No limits were placed on the age of the subjects. Letters to the editor, responses to previous articles, and expert opinions were not included in the review. The original search returned 91 articles. Twenty-three articles met the criteria for review on the basis of their abstracts. An additional eight articles were found to not meet the inclusion criteria (letters and expert opinion, reliability studies on normal subjects, evaluative descriptions) when their full text was reviewed, and three articles were not available as full text. A total of 12 articles are included in this review. From these articles, three main themes emerged: therapeutic interventions, surgical reconstruction, and robotic developments. A summary of these findings is included in Table 1.

Results

Therapeutic Interventions

Franke et al. [17] conducted a retrospective analysis of arm–hand skilled performance on a long-term cohort from

inpatient rehabilitation. They included 55 patients with tetraplegia from eight rehabilitation centers in the Netherlands over 5 years. Arm–hand skilled performance was assessed using the Van Lieshout test, short version (VLT-SV) at the initial admission of the patients, after 3 months, and at discharge from inpatient rehabilitation, and 1 and 5 years thereafter. Data on only 29 patients were available at the 5-year time point. The patients' mean age was 38 years, 73 % of the patients were male, 89 % of the patients had high cervical (C3–C6) injuries and 11 % of them had low cervical (C7–T1) injuries, and 69 % of the injuries were motor complete injuries [American Spinal Injury Association impairment scale (AIS) A/B] and 31 % were motor incomplete injuries (AIS C/D). The mean score on the VLT-SV was found to significantly increase during inpatient rehabilitation, but did not significantly change at the 1 and 5-year follow-ups. Incomplete lesion, high UE motor score, and no pain in the tested UE were found to have a positive relationship with the VLT-SV score. Lesion level (high or low cervical), age, and gender were not significantly related to the VLT-SV score. No specific information was provided about the interventions patients received during rehabilitation. Franke et al. acknowledge that the large number of patients lost to follow-up may have compromised the outcome, but this is not uncommon in long-term longitudinal studies. They also suggest that, given the lack of progress following discharge from inpatient rehabilitation, earlier consideration for surgical intervention is appropriate. The average time from inpatient admission to discharge in this study was 58 weeks. This is a significantly longer length of stay than is typical in the USA, and the recommendations should, therefore, carry with them some degree of caution.

Hesse et al. [18] published a case report regarding the use of surface magnets and their efficacy for facilitating increased independence with self-feeding after SCI. In this single case, the patient was a 56-year-old man with C7–T1 AIS A SCI 21 months previously. Prior to the intervention, he required maximal assistance for self-feeding using a universal cuff and had frequent spills when attempting self-feeding. Hindered by social stigma and energy demand for self-feeding, he typically relied on his wife to complete this aspect of his self-care. As the intervention, Hesse et al. attached a series of 6-mm-diameter and 3-mm-thick magnets to the patient's skin with self-adhesive tape over the radial aspect of middle phalanx of the third digit, over the second digit metacarpal, and at thumb interphalangeal joint. Immediately after the magnets had been secured, the patient was able to manipulate a fork and spoon, leading to less effort for self-feeding, an increased ability to pick food up with the utensils in a neutral forearm position, and greater success in bringing the food to his mouth without spills. Hesse et al. concluded that the introduction of

Table 1 Summary of key findings in reviewed articles

Authors	Year	Methods	No. of subjects	Patient demographics	Conclusions
Therapeutic interventions					
Franke et al. [17]	2013	Longitudinal cohort. In-patient rehabilitation, measured at the beginning, throughout, and 1 and 5 years later	55, only 29 at 5 years	40 men, 18–64 years old, 49 C3–C6, 6 C7–T1, 38 motor complete	Mean scores on VLT-SV increased during inpatient rehabilitation, but did not significantly change after rehabilitation. Incomplete lesion, high starting motor score, and no pain were associated with improved outcomes. Gender and injury level had no significant effect on the score
Hesse et al. [18]	2012	Single case study	1	56-year-old man, C7–T1 AIS A 21 months after injury	Magnets were adhered to the patient's skin over the radial aspect of the middle phalanx of the third digit, the second digit metacarpal, and at the thumb interphalangeal joint. Immediately the patient was able to manipulate a fork and spoon, leading to less effort for self-feeding and increased dexterity with cutlery
Larson and Denison [19••]	2013	Prospective, nonrandomized, nonblinded study of intensive ABT with and without OMA	23	7 OMA: 6 tetraplegia, 1 paraplegia; 6 motor complete: 5 tetraplegia, 1 paraplegia; 10 other: 2 tetraplegia, 8 paraplegia. All AIS, chronic (5.1 years), 30.1 years old	Mean therapy dose 137.3 h; motor scores improved in the first 60 days, but sensory scores did not. Incomplete tetraplegia or paraplegia was associated with better recovery. OMA made no difference
Tester et al. [20]	2012	Cohort study. Partial body weight treadmill walking. Bilateral 3D ground reaction forces and joint kinematics were assessed during two categories of CWS	22	11 with iSCI AIS D and 11 controls without neurological injury. SCI subject demographics: 46 years old, 39 months after SCI, C4–T3 AIS D, ISNCSCI LEMS of 46/50, and ISNCSCI UEMS of 44/50. Mean age for controls was 37 years.	Patients with iSCI produce a 1:1 ratio of arm swing cycle per gait cycle regardless of speed, whereas controls produce a 2:1 ratio at slow CWS and transition to a 1:1 ratio at fast CWS. Shoulder and hip coordination is present but is not speed-dependent after iSCI. Hip and arm swing amplitudes remain speed-dependent after iSCI
Surgical reconstruction					
Merenda et al. [24•]	2012	Retrospective medical record review of patients after biceps-to-triceps tendon transfer	12	All tetraplegia, age 14–21 years	67 % experienced tendon rupture, 33 % experienced attenuation Potential causes were surgical techniques, rehabilitation, co-contraction, poor compliance, and medication
Bertelli and Ghizoni [21]	2012	Single case study. Brachialis to triceps nerve transfer	1	53-year-old man with central cord, 5 months after a fall	Transferred brachialis branch to triceps nerve. Immobilized 1 week. No therapy followed. At 3 months elbow extension was M3, grade M4 at 6 months, and measured at 5 kg at 1 year. Elbow flexion strength fully recovered to the baseline at 1 year

Table 1 continued

Authors	Year	Methods	No. of subjects	Patient demographics	Conclusions
Mackinnon et al. [22]	2012	Single case study. Bilateral nerve transfer of brachialis nerve to the AIN	1	71-year-old man, 23 months after SCI, C7 AIS A. ICSHT grade 5 with no active pinch or grip bilaterally	Active movement began emerging 8 months postoperatively on the left and at 10 months on the right. Increased function on the left with the ability to self-feed and move the wrist but little functional improvements on the right
Fridén et al. [23]	2012	Cohort study. EDM tendon transfer to APB for palmar abduction of thumb.	15	7 women, 8 men with C5–T1 SCI. Mean age 43.9 years and 54.2 months after injury	Patients obtained increased active grasp and release and improved independence with self-feeding and dressing self-care. Active thumb opening increased. Average active plamar abduction of the thumb was 45° postoperatively. 14 of 15 participants could direct and coordinate lateral pinch
Gan et al. [25]	2012	Single case study. Implantation of SRS neuroprosthesis.	1	52-year-old man, C6–C7 SCI with weak tenodesis grasp. 10 years after injury	Active grasp was restored. The patient was able to hold a jug containing 1 L of water, and shake hands. The patient utilized the grasp component for 60–70 % of device use and used the device from 2 to 56 h per month. Fine manipulation is better without the SRS owing to decreased ability to grade contraction strength, leading to decreased dexterity. Concluded that SRS has greater selectivity than other neuroprostheses because it is less invasive, current is routed directly to nerves, and it has fewer external components
Robotic developments					
Scott and Vare [26]	2013	Cohort study. Sensor monitored head motion controlled virtual arm to targeted tasks	18	23–63 years old, 13 with cervical SCI	16 of 18 subjects were able to successfully use the controller to complete on-screen tasks. Horizontal and vertical movement, movement perpendicular to the coronal plane, radioulnar deviation, and pronosupination of the hand were considered
Yozbatiran et al. [27•]	2012	Single case study. Bilateral upper extremity training using the MAHI Exo-II	1	28-year-old woman, C2 AIS C, 29 months after SCI. Brown–Séquard syndrome	Increase in right wrist extensor, right finger flexor, and left finger abductor strength. Increase in ARAT on the left by 8 points, decrease in the Jebsen-Taylor hand function test total time from 151.64 to 80.4 s on the left, and increased left arm and left hand function. No functional improvement on the right.

Table 1 continued

Authors	Year	Methods	No. of subjects	Patient demographics	Conclusions
Zariffa et al. [28]	2012	Multicenter pilot study using robotic intervention via the ArmeoSpring	12	C4–C6 AIS A–D, with mean age of 43.3 years, and 75.25 days after injury. The nonrehabbed arm served as the control	At discharge, GRASSP sensibility subscore increased by 10 points for intervention limbs and 1.5 points for control limbs. Increases were greater for those with some distal function at the baseline. No significant differences were found in other assessments or between those in motor complete and motor incomplete groups

ABT activity-based physical therapy, *APB* abductor pollicis brevis, *AIN* anterior interosseous nerve, *AIS* American Spinal Injury Association impairment scale, *ARAT* Action Research Arm Test, *CWS* comfortable walking speed, *EDM* extensor digiti minimi, *GRASSP* Graded and Redefined Assessment of Strength, Sensibility, and Prehension, *ICSHT* International Classification for Surgery of the Hand in Tetraplegia, *iSCI* incomplete spinal cord injury, *ISNCSCI* International Standards for Neurological Classification of Spinal Cord Injury, *LEMS* lower extremity motor score, *OMA* olfactory mucosa autograft, *SCI* spinal cord injury, *SRS* Stimulus Router System, *UEMS* upper extremity motor score, *VTL-SV* Van Lieshout test, short version

surface magnets could be used to increase the independence of self-feeding in a person with decreased hand function due to SCI with immediate results.

Larson and Dension [19••] compared outcomes of patients with and without olfactory mucosa autograft (OMA) participating in intensive activity-based physical therapy (ABT), intervention that typically includes repetitive upper and lower limb motor activation. Although specific UE interventions were not discussed, overall motor and sensory findings associated with the International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI) were reported. Twenty-three patients participated in the study. Seven underwent OMA and six were control-matched to the OMA group on the basis of neurological level, impairment level (AIS), gender, time since injury, and age. Ten other patients, who were participating in the ABT program, were also included. On average, patients were 30.1 years old and had experienced their injury 5.1 years previously. Thirteen patients were tetraplegic and 14 were AIS A. On average, patients had undergone OMA 3.7 months previously. Patients received 3 h of ABT, three to five times per week for a minimum of 3 months. Interventions, optimized for the individual at the discretion of the therapist, included weight-bearing, balance training, standing/pregait, body-weight support treadmill training, mat mobility, biofeedback, whole-body vibration, musculoskeletal interventions, and functional electrical stimulation cycling. Over the duration of the study, each patient received an average of 137.3 total hours of therapy. Total motor score for all subjects improved significantly from the initial evaluation to 60 days and from the initial evaluation to discharge (average +5.5 points), regardless of therapy duration. Changes in the UE motor score and LE motor score were also

statistically significant at each of these time points, with average increases of 5.9 and 3.2 points respectively. There was no significant difference between the OMA, matched control, and other groups in total motor score, UE motor score, or LE motor score at any time point. Statistically significant improvements in total light touch scores occurred from the initial evaluation to 60 days, but not from the initial evaluation to discharge. Total pin prick and UE, trunk, LE light touch, and pin prick scores did not significantly change over the course of the study. Five subjects who were motor complete (AIS A/B) at the initial evaluation were motor incomplete (AIS C/D) at discharge. Two of these subjects had OMA, two were matched controls, and one was in the other group. Larson and Dension concluded that intensive ABT was effective at promoting motor, but not sensory, recovery and that the magnitude of the gains in these patients is significant given their chronicity. Patients with incomplete SCI (iSCI) or paraplegia demonstrated greater recovery. Patients who underwent OMA did not have greater motor or sensory recovery or a greater rate of recovery as compared with patients who received only therapy.

Tester et al. [20] completed a preliminary study assessing differences in arm swing and leg coordination during partial body weight supported walking over a treadmill in individuals with iSCI compared with those individuals without neurological injury. They specifically looked at characterization of arm and leg coordination at comfortable walking speeds (CWS), including angles, durations, amplitudes, and variability during 30-s walking bouts. Bilateral 3D ground reaction forces were recorded and 3D joint kinematics were collected using a Helen Hays marker set and a 12-camera motion analysis system. The individuals with iSCI in this study had a mean age of

46 years, had experienced iSCI 39 months previously, and had C4–T3 AIS D injuries. Their mean ISNCSCI LE motor score was 46/50 and their mean ISNCSCI UE motor score was 44/50. Tester et al. discovered that patients with iSCI produce a 1:1 ratio of arm swing cycle per gait cycle regardless of CWS, whereas the control subjects produce a 2:1 ratio at a slow CWS and transition to a 1:1 ratio at fast CWS. They further found that in iSCI, shoulder and hip coordination is present but is not speed-dependent, whereas hip and arm swing amplitudes are speed-dependent after iSCI. They concluded that the 1:1 arm to gait-cycle ratio despite CWS may be a compensatory strategy used by those with iSCI to improve walking function to enhance their balance and trunk strength. It was further concluded that a high degree of coordination occurs during treadmill walking after iSCI, regardless of CWS, and that arm swing should be encouraged to enhance the neural components involved in interextremity walking coordination.

Surgical Reconstruction

Bertelli and Ghizoni [21] described a brachialis to triceps nerve transfer in a patient with central cord syndrome. The patient was 53-years old, 5 months after a fall, and had cervical decompression and stabilization, with diffuse right UE weakness. A branch of the brachialis was transferred to the triceps medial head motor branches. Postoperatively, the patient was immobilized for 1 week. He received nandrolone decanoate for 3 months, followed by a 1-month drug holiday. This was repeated four times. Three months later, the patient had recovered M3 elbow extension strength, had M4 strength at 6 and 12 months after surgery, and elbow extension strength was measured at 5 kg. Elbow flexion was maintained throughout and returned to the baseline strength after 12 months with noted hypertrophy of the brachioradialis. No other UE muscles showed changes over this period. Bertelli and Ghizoni concluded that of the branch of the brachialis nerve is a viable strategy for surgical reinnervation of functional elbow extension.

Mackinnon et al. [22] conducted a single case study evaluating the efficacy of nerve transfers for the restoration of hand function after SCI. The patient was a 71-year-old man 23 months after a C7 AIS A SCI and who had no active pinch or grip prior to surgery. He underwent bilateral nerve transfers of the brachialis nerve to the anterior interosseous nerve (AIN) and engaged in hand therapies for an undisclosed time. Active movement began emerging in the flexor pollicis longus and flexor digitorum profundus at 8 months postoperatively in the left distal extremity and at 10 months postoperatively in the right distal extremity. The patient gained sufficient active movement to be able to complete self-feeding and writing tasks with the left UE without adaptive equipment. The right UE showed less

functional improvement at the completion of the 12-month follow-up period. Mackinnon et al. concluded that the results indicate successful reinnervation of the AIN and some restored finger and thumb flexion. They further concluded that a time frame for performing nerve transfers following SCI is not a factor as it is thought to be in peripheral nerve injuries such as those to the brachial plexus and should be considered in the restoration of function in the SCI population.

Fridén et al. [23] examined the efficacy of tendon transfers in restoring palmar abduction of the thumb using the extensor digiti minimi to abductor pollicis brevis in individuals with chronic tetraplegia. In addition to the tendon transfer, participants underwent two to four additional procedures to reconstruct grip through various surgical procedures. There were 15 participants in the study; they had a mean age of 43.9 years, had experienced SCI 52.2 months previously, and had injuries at the C5–T1 level. The post-operative regimen included mobilization of flexion apparatus to activate grip in conjunction with protective splinting between skilled hand therapies. Task-oriented and self-care training started at 4 weeks postoperatively. At follow-up, patients demonstrated improved active grasp and release, and increased independence with self-feeding and dressing, and active thumb opening increased from 2.5 to 9.0 cm on average. Those without active web space opening prior to surgery recovered 9.1 cm, whereas the active web space opening of those with active web space opening prior to surgery increased by 2.9 cm. Fourteen of the 15 participants could direct and coordinate lateral pinch at follow-up. Finally, grip strength and lateral pinch strength were not recordable in 13 of the 15 patients prior to surgery but were 2.2 kg and 1.3 kg, respectively, at follow-up. Fridén et al. reported no adverse response in participants other than an extensor digiti minimi tendon rupture in one patient.

In 2012, Merenda et al. [24•] conducted an analysis of potential causes of rupture following biceps-to-triceps tendon transfer in 12 patients. All 12 patients were males with tetraplegia (C4–C6) who underwent biceps-to-triceps tendon reconstruction with rupture or attenuation. The mean age at injury was 16 years. The mean age at the time of transfer was 18 years. The patients' surgery and post-operative regimen followed a well-established protocol. The surgical technique was consistent, except for the method of fixation. All patients received antibiotics post-operatively, most commonly cephalosporin. Five patients were prescribed fluoroquinolones during their inpatient stay after transfer. Diagnosis of rupture was made by physical examination. Overt rupture, with complete loss of elbow extension, was found in eight patients. Attenuation was confirmed in four patients by the development of a significant lag. The length of time from surgery to rupture or attenuation ranged from 3 to 10 months. All ruptures

happened at home, during various activities. Surgical technique could not be associated with rupture or attenuation in this cohort. Elbow flexion was limited during rehabilitation, including protective bracing and modest weekly increases unless there was an extension lag, so it was not likely a cause. Patient compliance was also ruled out as a potential contributor. The most likely factors contributing to rupture and attenuation, as determined by Merenda et al., were co-contraction and the use of fluoroquinolones. Inadvertent contraction of the biceps into flexion, during active extension, could cause early gap formation, insufficient healing, and rupture or attenuation. Fluoroquinolones carry an FDA warning related to tendon disorders, reported at a rate of 15–20 per 100,000 patients. For this reason, Merenda et al. suggest that patients be counseled on the risks associated with fluoroquinolones and that alternative antibiotics be explored for patients undergoing tendon transfer.

Robotic Developments

Gan et al. [25] conducted a single case study on the effectiveness of a new implantable neuroprosthesis that aims to assist with grasp and release, the Stimulus Router System (SRS). The patient was a 52-year-old man 10 years after C6–C7 SCI with weak tenodesis grasp on the surgical side. The surgical procedure consisted of implantation of six leads and connection of the AIN to the nerve cuff of the SRS system. The patient was splinted postoperatively for 10 days and at 6 weeks postoperatively. He was fitted with a wireless earpiece and wristlet stimulator which controlled four surface electrodes that communicated with the six implanted leads. Tooth clicks detected by the earpiece operated the stimulation delivered by the wrist cuff to open and close the hand. The patient participated in telesupervised exercise sessions five times a week for 6 weeks, starting with 15-min sessions and progressing to 1-h sessions, and then the sessions took place monthly thereafter until 6 months postoperatively. At 6 months, the patient was able to hold a jug containing 1 L of water and easily shake hands. The patient utilized the grasp component for 60–70 % of device use and used the device from 2 to 56 h per month. The patient was unable to independently don the device and he reported a preference not to use the device during fine manipulation activities since his motor control was better without the SRS owing to the inability to grade contraction strength with the SRS. Additionally, the patient experienced compression of the AIN leading to swelling and soreness, which the investigators believed to be a result of functional use of the system occurring too early. Gan et al. concluded that the SRS has greater selectivity than other neuroprostheses because it is effective, is less invasive and has fewer external components

than other neuroprostheses, and has current which is routed directly to nerves.

Scott and Vare [26] reported on their development of a novel five-degree-of-freedom user controller for neuroprostheses. A sensor was used to detect head position changes, which were used to control an on-screen upper limb representation. Patients were asked to complete tracking tasks to manipulate the forearm and hand position in 3D space. Horizontal and vertical movement, movement perpendicular to the coronal plane, radioulnar deviation, and pronosupination of the hand were considered. Shoulder and elbow motions were not represented. There were 18 participants in the study: 13 participants had AIS A SCIs at levels C4–C6 and there were five noninjured subjects. Participants engaged in at least three trials of each tracking test and mean scores were recorded. Two of the 13 participants with SCI were unable to complete the tracking tests owing to decreased cervical range of motion. Non-injured participants were significantly faster than injured subjects when times to complete tracking tasks were analyzed and they completed the tests with few errors. Additionally, Scott and Vare discovered that those with C5–C6 injuries were significantly faster than those with C4 injuries. Finally, those with increased cervical range of motion performed better than those with less. These findings suggest that this type of controller mechanism was an effective and enjoyable option for promoting independent computer use for individuals with C4–C6 complete SCI.

Yozbatiran et al. [27•] reported on the effectiveness of robotic training in a single case study of a 28-year-old woman with an iSCI. The patient was diagnosed with C2 AIS C SCI, was 29 months after the initial onset of injury, and had a Brown–Séquard presentation. The robotic training focused on high-repetition, single joint movements using the MAHI Exo-II for 12 sessions of 3 h in 4 weeks; training was conducted bilaterally. Following the 4 weeks of robotic training, Yozbatiran et al. reported an increase in the subjects' American Spinal Injury Association UE motor score by one grade in each of the following muscle groups: right wrist extensors, right finger flexors, and left finger abductors. The patient also demonstrated an increase in the Action Research Arm Test score on the left by eight points, a decrease in the Jebsen–Taylor hand function test total time from 151.64 to 80.4 s on the left, and a subjective increase in left arm and left hand function. No functional improvement was noted in the outcome measures for the right UE.

Zariffa et al. [28] conducted a multicenter pilot study examining the feasibility and efficacy of upper limb robotic rehabilitation in those with subacute cervical SCIs. The investigators used ABT principles through unilateral robotic rehabilitation using the ArmeoSpring. The patient's nonrobotic rehabbed limb served as the control group. The

study consisted of 12 patients with C4–C6 AIS A–D SCI who had a mean age of 43.3 years and mean time after injury of 75.25 days. Participants engaged in an average of 16.1 sessions of robotic training, lasting 1 h each, in 5.2 weeks. The patients received conventional physical and occupational therapies bilaterally during the trial period. Zariffa et al. concluded that there was a decrease in the amount of time a therapist needed to be actively involved in the robotic training once a program had been established. Two weeks after completion of the robotic training, the Graded and Redefined Assessment of Strength, Sensibility, and Prehension (GRASSP) sensibility subscore increased by ten points for the intervention limbs and by 1.5 points for the control limbs. Increases were greater for those with some distal function at the baseline. No significant differences were found in other assessments (Action Research Arm Test, grip dynamometry, or range of motion), and no significant difference was found in results from motor complete and motor incomplete groups. Zariffa et al. concluded that their pilot study found that individuals with some preserved hand function after SCI may be better candidates for robotic rehabilitation.

Conclusion

Slow but steady gains are being made in UE rehabilitation and restoration following SCI; however, there continues to be no consistent intervention protocol or algorithm for remediation following paralysis. Activity-based therapeutic interventions, focusing on high repetition and specific patterning, continue to gain popularity and show support for promoting functional recovery in skills such as self-feeding and handwriting as well as neurologic recovery using standardized assessments [17, 18, 19•, 20]. It is largely accepted that those with incomplete lesions have greater recovery, and now it is apparent that the magnitude of recovery is independent of the time since the injury. Surgical reconstruction, including muscle and nerve transfers, is gaining popularity in restoration of upper limb function following SCI [21–23, 24•]. Techniques are evolving from evidence and successes in the treatment of brachial plexopathies and peripheral nerve injuries. There can be complications following these procedures, including insufficient healing, rupture, attenuation, swelling, and pain. In addition, the studies reviewed here reveal inconsistent results even among subjects who underwent identical procedures bilaterally, which points to the multifactorial contribution to a successful outcome and needs to be explored further. Robotic interventions were effective in increasing strength, coordination, and range of motion in individuals with cervical SCIs and patient's reported enjoyment with training [18, 25, 26, 27•]. Robotics is a promising avenue for meaningful

restoration of upper limb use, but it has limited practical applications and major technical pitfalls at this time.

Further research is needed to make great strides in UE rehabilitation and restoration following SCI. This includes increasing sample sizes, developing a consistent series of outcome measures for comparison across studies and interventions, and a larger volume of published research studies in general. Until this occurs, there will continue to be no standard intervention set for the UE following SCI, and a combination of approaches should be considered.

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