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Effectiveness of myoelectric wearable orthoses for upper extremity functional recovery in spinal cord injury– a pilot study

Ghaith J. Androwis[1,2*], Amanda Engler[1], Courtney Craven[1], Julie Eng[1], Alfonse Gaite[1], Sameer Rana[1], Salli AlRabadi[1], Juan Ramirez[1], Remy Salloum[1], Christian Alvarez[1], Michael Wassef[1], Mohammed Huzien[1], Brittany Snider[3], Steven Kirshblum[3] and Guang H. Yue[1,2]

Abstract
Spinal cord injury (SCI) can lead to severe upper extremity (UE) impairments, limiting activities of daily living (ADLs) and independence. The overall goal of this pilot study was to evaluate a myoelectric-powered wearable orthosis (MPWO, MyoPro, MyoMo Inc.) for improving handgrip strength and active range of motion (AROM) in persons with chronic incomplete SCI. Ten participants with chronic cervical iSCI (mean age 53 years, AIS B-D) were randomized into three groups: Clinic-only MPWO (*n* = 3), Home + Clinic MPWO (*n* = 4), or Control traditional occupational therapy (TOT), (*n* = 3). All groups received 18 training sessions over 6 weeks (3×/week, ~60 min/session). Outcome measures included handgrip AROM and maximal grip force, assessed before and after training. Participants in the MPWO groups demonstrated substantial improvements in handgrip AROM and strength compared to baseline. On the MPWO-trained side, average increases of ~30–37% were observed in maximum handgrip AROM and ~28–30% in maximum grip force after training. The Home + Clinic MPWO group tended to exhibit the greatest gains. The non- MPWO trained (contralateral) side in the MPWO groups also showed indirect improvements, with modest increases of ~7–12% in AROM and grip force measures (suggesting a possible cross-education effect). In contrast, the TOT control group showed minimal changes (< 10% on average). These preliminary results indicate that UE-MPWO–assisted rehabilitation – especially when combined with at-home use – may enhance hand function in persons with chronic cervical SCI.

Keywords Spinal cord injury, Upper extremity, Myoelectric orthosis, Rehabilitation, Active range of motion.

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*Correspondence:
Ghaith J. Androwis
gandrowis@kesslerfoundation.org
[1] Center for Mobility and Engineering Research at Kessler Foundation, West Orange, NJ, USA
[2] Rutgers New Jersey Medical School Department of Physical Medicine and Rehabilitation, Newark, NJ, USA
[3] Kessler Institute for Rehabilitation and Rutgers New Jersey Medical School Department of Physical Medicine and Rehabilitation and the Kessler Foundation, Newark, NJ, USA

Introduction

Spinal cord injury (SCI) is a medically complex and life-altering condition that often results in permanent physical disability. In the United States, approximately 18,400 new cases of traumatic SCI occur annually [1], with nearly 60% involving the cervical spinal cord. Cervical SCIs frequently result in partial or complete paralysis, sensory deficits, and impaired motor control in both the upper and lower extremities (UEs and LEs), contributing to significant functional dependence [1, 2]. The severity and distribution of these impairments are largely determined by the level and extent of spinal cord damage [1, 3]. Individuals with high-level cervical injuries often experience profound limitations in upper limb function, significantly affecting their ability to perform activities of daily living (ADLs), reducing independence, and negatively impacting quality of life (QOL) [4].

Restoration of upper extremity motor function is a critical rehabilitation priority for individuals with cervical SCI. While several therapeutic interventions exist—including traditional physical therapy, functional electrical stimulation, and static orthoses for tone and contracture management—there remains a lack of wearable, powered devices specifically designed to restore wrist, hand, and elbow function in this population [3, 4]. Recent research has explored task-specific training, including robotic-assisted movement therapy, to promote neuroplasticity and improve functional outcomes in individuals with incomplete SCI (iSCI) [2–9]. However, the current evidence supporting these approaches is mixed, particularly regarding their effects on fine motor control and translation to improve ADL performance. Indeed, recent systematic reviews highlight both promising gains and remaining limitations of robot-assisted training in SCI [8, 10]. Additionally, such interventions are often restricted to controlled clinical or laboratory environments and are not readily adaptable for home use.

A promising alternative is the myoelectric-powered wearable orthosis (MPWO), such as *MyoPro* (MyoMo Inc., Boston, MA), which was developed to assist individuals with motor impairment in performing functional UE movements in both clinical and home settings. The device provides powered assistance for hand grasp/release and elbow flexion/extension, driven by the user's residual voluntary muscle activity, as detected through surface electromyographic (EMG) signals recorded by integrated sensors. These signals, even when weak, are amplified by the system to generate functional movement. This feature makes MyoPro particularly suitable for individuals with iSCI who retain partial but insufficient muscle activation.

Compared with other wearable robotic orthoses (WROs), MyoPro offers several distinct advantages:

(i) it is lightweight (~ 4 lbs) and portable, enabling use in home and community settings for functional tasks such as feeding, object transport, and personal care [11]; (ii) it operates in response to volitional muscle signals, promoting user engagement and intention-driven control; (iii) active user participation in movement is known to support motor learning and neuroplastic reorganization; and (iv) it is explicitly designed to assist elbow, wrist, and hand functions—areas that are commonly impaired in individuals with cervical SCI and are challenging to rehabilitate via conventional methods.

Given the established relationships between UE function and QOL, independence, self-esteem, and community reintegration in neurologically impaired populations [12, 13], interventions that enhance UE function may have broad therapeutic and psychosocial benefits. Although most existing efficacy data for MPWOs are derived from studies in poststroke populations [9, 14–16], preliminary case reports in individuals with SCI have demonstrated improvements in strength, muscle tone regulation, and functional use of the affected limb [17, 18]. For example, a four-week intervention using orthotic assistance was associated with significant gains in manual muscle testing of wrist extensors, finger flexors, and finger abductors. Osuagwu et al. reported hand function improvements using a home-based robotic glove [19]. Several other adjunctive robotic therapy studies have reported modest motor gains in individuals with tetraplegic SCI, for instance, Jung et al. (2019) found improvements in upper-limb strength, functional independence, and prehension when robotic training was added to standard occupational therapy [20]. The present study aimed to systematically evaluate the effects of MyoPro MPWO on upper extremity motor function in individuals with incomplete SCI (iSCI). By integrating objective assessments of handgrip angular position with handgrip force, we sought to comprehensively measure functional improvements and explore the potential for enhanced ADL performance and QOL resulting from MPWO use.

Materials and methods

Experimental design

The current study represents a three-arm, randomized pilot trial (RCT) examining the effects of 6 weeks of MPWO training under two different conditions compared with 6 weeks of traditional occupational therapy (TOT) in individuals with chronic cervical SCI. Participants were randomized to one of three groups: Clinic-only MPWO, Home + Clinic MPWO, or TOT control.

Participants

Participants were recruited directly from the Kessler Institute for Rehabilitation, referrals made by participants' clinicians, and a database of previous research participants. The participants underwent initial telephone screening to confirm that their age was between 18 and 80 years and received a physiatrist-confirmed definitive SCI diagnosis, performing the neurological examination according to the International Standards of Neurological Classification of SCI, to determine the neurological level of injury and SCI classification using the ASIA Impairment Scale [21]. Participants with iSCI at the cervical level (C1-C8) were included. Study recruitment and participation are presented in Fig. 1. Seventeen individuals were screened; 14 met inclusion criteria and were enrolled (Fig. 1). Participants were randomly allocated to Clinic-only MPWO (*n* = 4), Home + Clinic MPWO (*n* = 4), or control TOT (*n* = 6). Four participants withdrew during the study (1 from Clinic-only MPWO and 3 from TOT), resulting in a final analyzed sample of 10 participants (Clinic-only MPWO *n* = 3; Home + Clinic MPWO *n* = 4; TOT *n* = 3). Randomization was performed using a computer-generated sequence. All participants provided written informed consent, and the study was approved by the Kessler Foundation Institutional Review Board. Among the 10 participants, 4 had greater impairment in the right upper limb (2 of whom were right-hand dominant), while 6 had a more impaired left upper limb and all were right-hand dominant). Each MPWO device was applied to the participant's more-impaired side when feasible. We did not stratify or analyze outcomes by hand dominance or affected side due to the small sample size.

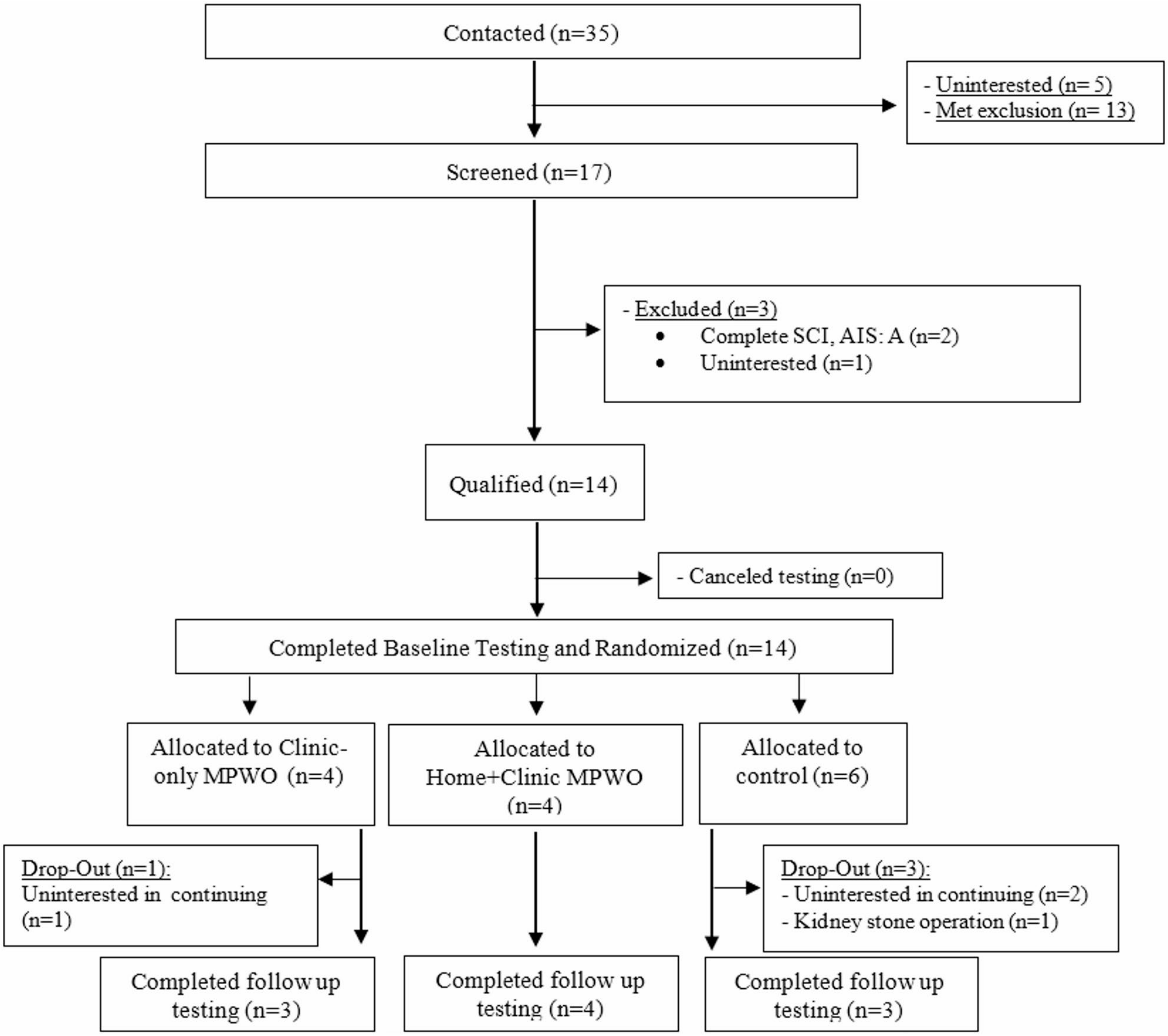

Fig. 1 CONSORT Diagram

Experimental procedure

Training was provided via UE-MPWO (for the clinic-only group and home + clinic MPWO group)

Participants in the MPWO groups received 18 upper-extremity training sessions in a rehabilitation research center (3×/week for 6 weeks, ~ 60 min/session) using the MyoPro UE-MPWO device. Each session was supervised by a licensed therapist and involved a customized training program with the orthosis. The in-clinic training protocol was identical for both MPWO groups. In the Home + Clinic MPWO group, participants were additionally provided with the MPWO device for unsupervised home use between clinic visits, and were instructed to perform functional exercises with the device at home for ~ 2 h per week in weeks 4–6 of the study. By contrast, the Clinic-only MPWO group used the device only during supervised sessions. The Home+Clinic MPWO group was the only group provided with a structured home exercise program using the device. However, none of the groups were restricted or explicitly instructed to avoid general physical activity or exercises outside the formal therapy sessions. Participants in the Clinic-only MPWO and Control/TOT groups were simply not provided with a specific home program, but they were allowed to continue their usual daily routines or self-directed activities.

The UE-MPWO device (Fig. 2) is a lightweight (~ 4 lb) wearable orthosis that affixes directly to the participant's arm and provides powered assistance for elbow flexion/extension and hand grasp/release via integrated motors [14]. The device enables a range of motion from 0° to 130° at the elbow, delivers up to 7 Nm of torque, and provides 1–2.7 Nm of torque to assist finger movements. This level of support allows users to lift objects weighing up to 8 lbs during elbow flexion tasks [14]. Control is achieved through the user's volitional muscle signals, detected by surface EMG sensors on the biceps/triceps (elbow) and forearm flexors/extensors (hand). Even weak EMG signals are amplified by the device to produce functional movement, enabling users with limited residual muscle function to perform assisted joint motions. These sEMG signals are continuously filtered and processed by the device's onboard control system, which generates joint torques proportional to the user's voluntary muscle activation. As a result, even low amplitude sEMG signals can be amplified to produce functional joint movements, enabling users with impaired motor control to perform assisted motions at the elbow and hand. During the first week of training, participants learned donning/doffing, practiced repetitive task drills, and incorporated the MPWO into multi-step functional tasks. Active training time with the device began at ~ 20 min per session in week 1 and was progressively increased by ~ 5 min each week, reaching ~ 45 min by week 6. Weeks 2–6 emphasized task-specific activities using the MPWO in ADL-oriented tasks (e.g. self-feeding, reaching to shelves, grasp/release of objects, grooming). Participants were

Fig. 2 Illustration of the myoelectric upper extremity MyoPro MPWO

encouraged to exert volitional effort during all movements, as the device would augment their active muscle contractions.

Training was provided following traditional occupational therapy (TOT) in the control group

Participants in the control group received 18 sessions of conventional OT over 6 weeks (frequency and session duration matched to the MPWO groups). TOT sessions consisted of standard-of-care UE rehabilitation techniques, including therapeutic exercise, active-assisted and passive ROM exercises, mirror therapy, neuromuscular facilitation, dynamic taping for support, manual therapies (massage), and task-oriented practice of functional activities, but no functional electrical stimulation (FES) was permitted. The TOT regimen was tailored to each participant's needs, typically focusing on the more-impaired arm while also incorporating bilateral movements (e.g., mirror therapy) to engage both sides. The intensity and progression of exercises in the TOT group were designed to parallel the MPWO training as closely as possible, minus the use of the powered orthosis. All TOT sessions were supervised by licensed physical therapists who continuously monitored participants and provided specific recommendations to discourage the use of compensatory strategies such as tenodesis grasp.

Baseline and post training evaluations

During the baseline and post training assessment sessions, the participants were seated in her/his wheelchair, and testing was conducted without the use of the UE-MPWO (Fig. 3). Measurements for each hand were made via a customized system including a 9-axis absolute orientation inertial measurement unit (IMU) sensor (Adafruit Bosch Sensortec, USA) for measuring hand angular position and a 1-DOF load sensor (Load Cell (0–20 kg), Calgary, Canada) for measuring handgrip forces.

The IMU sensor was attached to the distal end of the participants' hand (i.e., close to the fingertips) via Velcro straps on the four fingers (without the thumb). The participants' hand was placed on a force sensor gripper at the palm using a Velcro strap while keeping the hand's four fingers free to open and close (handgrip motion).

The participants sat approximately 60 cm from a monitor that displayed visual cues during testing trials. Testing started by displaying two red "X" letters representing each hand. The red "X" represents the visual cue for opening the hand and relaxing the forearm muscles. Next, a green "O" appeared on either the right or left side of the screen. This visual cue prompted the participants to grasp (close their hand) the force sensors maximally and hold them while the green letter was displayed. After that, two red "X" letters were displayed, cueing the participants to open the hand, which was in motion. A total of 30 green cues (15 for each side) were randomly presented. Each green cue lasted for 4 s before it was changed to a red cue. Red cues were displayed for a random duration (ranging between 2.3 and 4.3 s to minimize the learning effect).

Data analysis

A custom script using MATLAB 2024 (MathWorks, Inc.) was created to analyze the collected data. The hand angle-position and handgrip force measurements were filtered via a bidirectional zero-lag Butterworth low-pass filter (cutoff frequency = 10 Hz).

The data were segmented to include 15 grasp motions for each hand. Each handgrip was normalized to 100% activity cycle starting at 0% (when a motion cue (green circle) was presented to participants) and 100% (when the presented cue became a red X) (Fig. 3). Data from every trial was compiled and presented as the means and standard deviations.

To quantify precise changes in motor control, the hand angular position AROM and handgrip strength were analyzed further, and we extracted the maximum value (peak value) and average value between 30% and 70% of the active cycle (representing the plateau area at which participants were squeezing as prompted by the visual cues) (Fig. 4).

Statistical Analysis: Pre- and post-training values were recorded for each outcome. Due to the pilot sample size, we report effect sizes (Cohen's d) to describe within-group improvements. In addition, we conducted analysis of covariance (ANCOVA) to compare post-training outcomes between groups, using the baseline value as a covariate. For each outcome, adjusted post-intervention means (estimated marginal means) were obtained for each group. Group differences were tested with a two-tailed $\alpha = 0.05$ significance level. Partial eta-squared (η^2) was calculated to indicate effect size of group differences. A sensitivity analysis was conducted for each outcome with baseline values entered as covariates, confirming similar trends. This analysis allowed us to account for pre-treatment differences between groups. Due to the small sample, no correction for multiple comparisons was applied. All analyses were performed using SPSS v28.0.

Results

Descriptive characteristics

Ten participants were assigned to three groups (3 Clinic-only MPWO, 4 Home + Clinic MPWO, 3 TOT), and completed the study. All completed sessions as prescribed, and no adverse events were observed. (Fig. 1 presents the CONSORT diagram of participant flow, including group allocations and drop-outs.). The demographic and

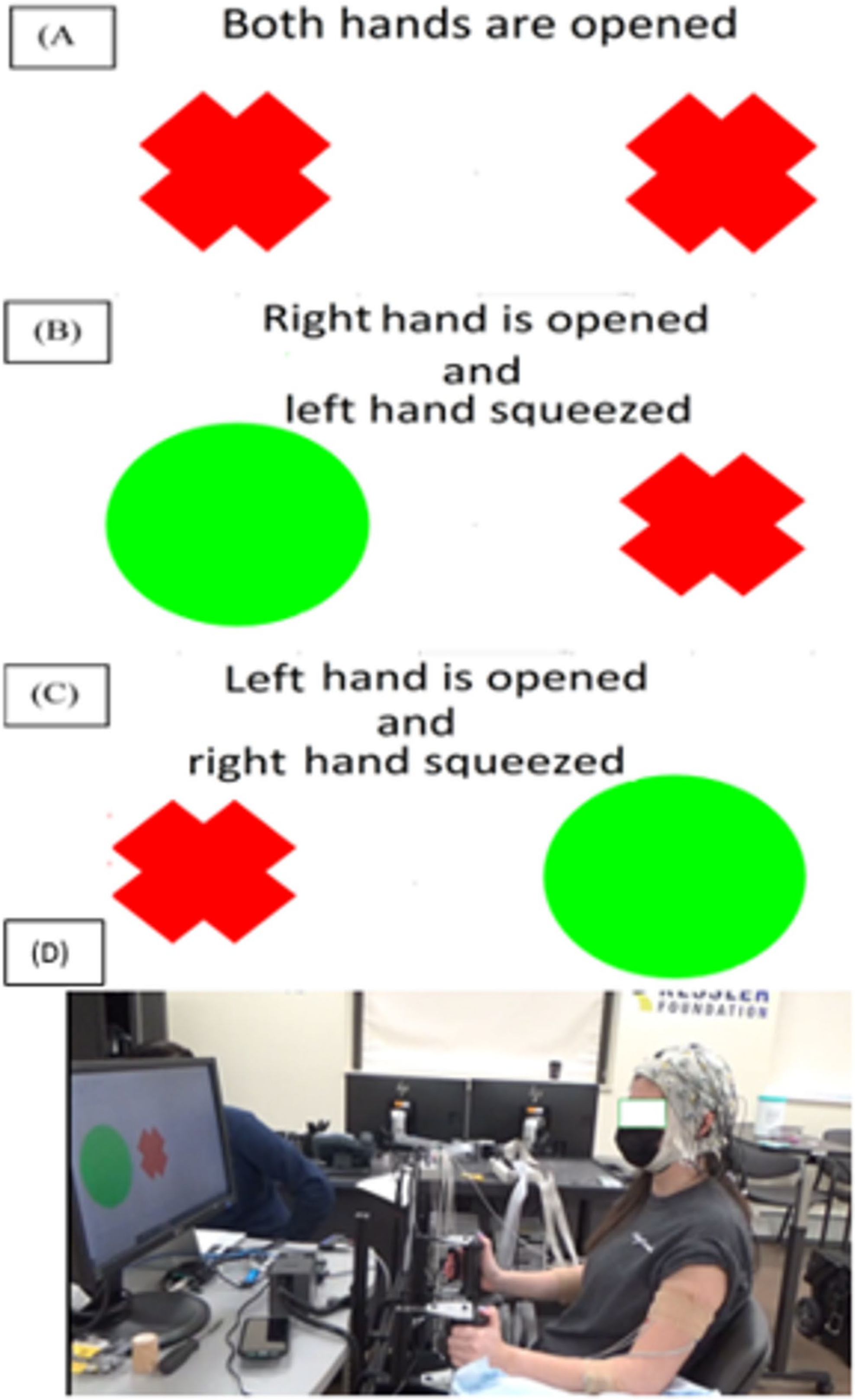

Fig. 3 Visual cues presented to participants during this evaluation. (A) two red X, cue participants to open both hand and relax. (B) left green circle and right red X cue the participant to squeeze their left hand and keep their right hand opened. (C) right green circle and left red X, cue the participants to squeeze their right hand and keep their left hand opened. (D) The participant is performing a task in the evaluation session

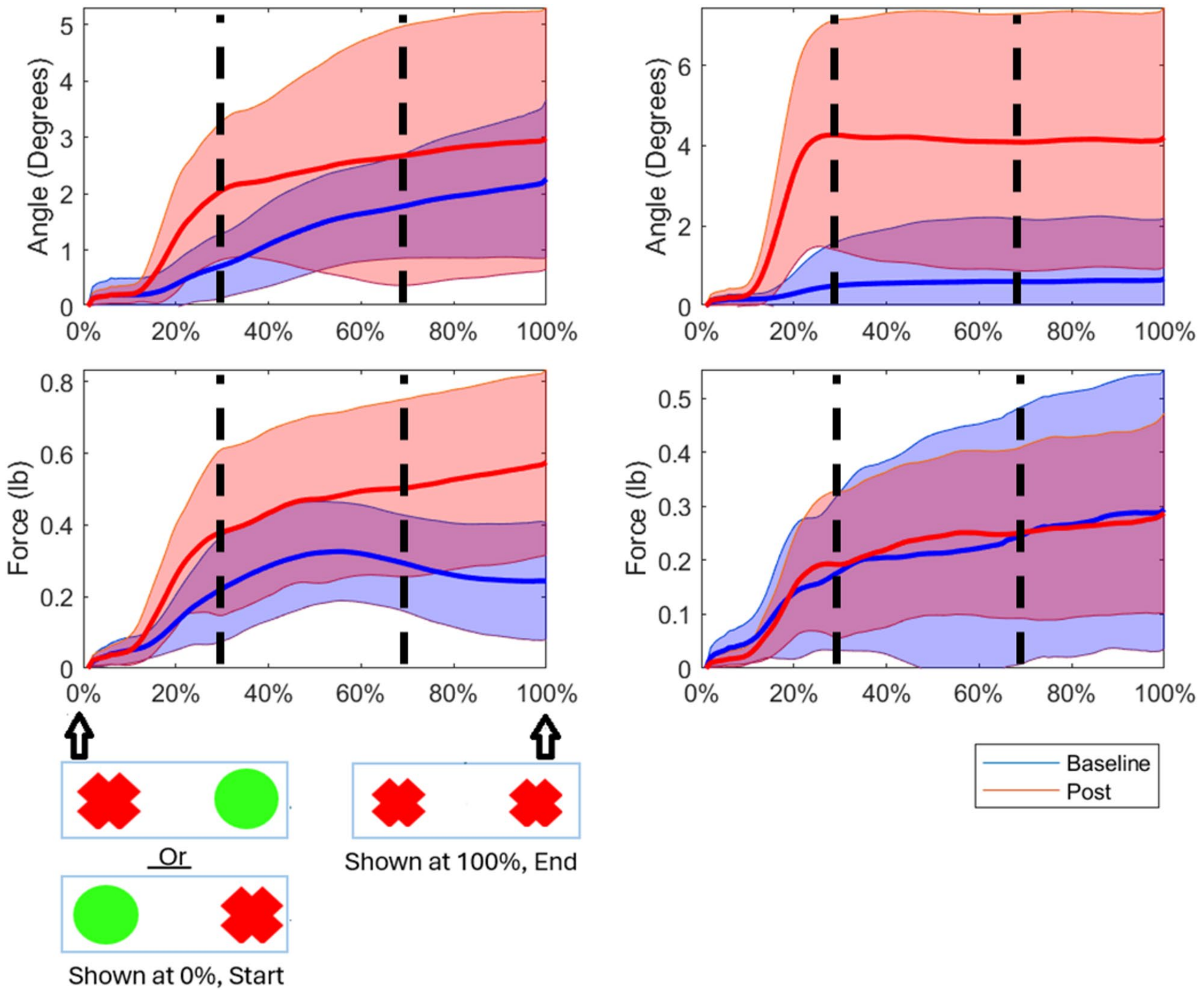

Fig. 4 An illustrative example from one participant, with top panels = ROM and bottom panels = force, and with color-coding for baseline (blue) vs. post (red). The x-axis percent represents the instance when a motion cue (green circle) was presented to the participant on either the right or left side (0%), and when the presented cue becomes a red X on both sides, the squeezing task is completed and concludes one sequencing activity cycle at 100%. Vertical dashed lines are representing the range that the average value between 30%-70% of the active cycle

clinical characteristics of the sample are presented in Table 1.

Adherence and compliance

Overall, applying UE-MPWO for UE movement training was successful in participants with iSCI with no adverse events during the study. All ten participants who were retained in the study attended all 18 MPWRO or TOT sessions over the 6-week period. With respect to compliance, all participants completed each session as prescribed across both conditions.

Primary outcomes

Data on the hand angular position AROM and handgrip force were analyzed further, and the maximum value (peak value) and average value between 30% and 70% of the active hand-squeezing cycle per group per time point are presented in Table 2; Fig. 4. These data are the results of evaluation at baseline (prior to the training sessions, blue color) and after 6 weeks of training via the MPWRO or TOT (red color in Fig. 4).

On average, participants in the MPWO groups (Clinic-only MPWO and home + Clinic MPWO) demonstrated large improvements in handgrip AROM and handgrip force post-MPWO training compared with baseline. On the MPWO trained side, there were improvements of 36.5% in the maximum handgrip AROM, 28.5% in the maximum handgrip force, 39% in the average activation of the handgrip AROM (between 30% and 70% of the active hand-squeezing cycle), and 30% in the average handgrip force activation (between 30% and 70% of the active hand-squeezing cycle). Furthermore, the

Table 1 Baseline demographic and clinical characteristics of 10 people with SCI

Participant	Gender	Age (year)	Neurological level of injury	AIS Grade	Months post injury	group assignment	Handedness	More Affected side
1	Male	32	C4	B	96	Clinic-only MPWO	Left	Right
2	Female	21	C6	D	30	Home + Clinic MPWO	Right	Left
3	Male	58	C2	C	119	Control	Right	Left
4	Male	40	C5	B	68	Clinic-only MPWO	Right	Left
5	Male	54	C4	C	15	Control	Right	Left
6	Male	54	C2	D	45	Home + Clinic MPWO	Left	Right
7	Male	47	C2	C	13	Home + Clinic MPWO	Right	Left
8	Male	62	C6	C	35	Home + Clinic MPWO	Right	Right
9	Male	45	C7	D	13	Control	Right	Left
10	Male	66	C4	C	29	Clinic-only MPWO	Right	Right

Table 2 Adjusted post-intervention handgrip AROM and strength outcomes (mean ± SE) for the three groups, with ANCOVA F-test results (df = 2,6)

Outcome Measure	Clinic-Only MPWO ($n = 3$) *Adj. Mean ± SE*	Home + Clinic MPWO ($n = 4$) *Adj. Mean ± SE*	Control (TOT) ($n = 3$) *Adj. Mean ± SE*	ANCOVA F(2,6)	*p*-value	Effect Size (Partial η^2)
Max AROM (°) – Trained side	22.18 ± 3.01	29.56 ± 1.69	32.65 ± 5.71	2.867	0.134	0.489
Max AROM (°) – Contralateral side	13.77 ± 3.56	13.14 ± 3.37	−10.90 ± 49.19	0.126	0.884	0.040
Max Grip (kg) – Trained side	2.12 ± 2.02	3.79 ± 0.64	11.27 ± 13.90	0.627	0.566	0.173
Max Grip (kg) – Contralateral side	0.52 ± 0.42	2.00 ± 0.24	−0.02 ± 0.94	5.409	**0.045***	**0.643**
Avg AROM (°) (30–70%) – Trained side	18.09 ± 3.05	28.00 ± 1.68	29.61 ± 6.30	4.673	0.060	**0.609**
Avg AROM (°) (30–70%) – Contralateral side	14.20 ± 3.28	11.93 ± 3.09	−15.60 ± 61.69	0.353	0.716	0.105
Avg Grip (kg) (30–70%) – Trained side	1.55 ± 1.68	3.23 ± 0.54	9.22 ± 12.92	0.702	0.532	0.190
Avg Grip (kg) (30–70%) – Contralateral side	0.40 ± 0.28	1.65 ± 0.17	−0.17 ± 0.73	8.289	**0.019***	**0.734**

Note: All data are presented as the mean (SE); MPWO = myoelectric-powered wearable orthosis; TOT = traditional occupational therapy; AROM = active range of motion; Grip = handgrip force. Negative adjusted means reflect slight decreases from baseline. The "trained side" refers to the arm that received MPWO training, and "contralateral side" refers to the opposite arm

non-MPWO trained side in the same groups also demonstrated indirect small improvements. There were 7%, 6.5%, 7.5%, and 12% improvements in handgrip maximum AROM, handgrip maximum forces, average activation of handgrip AROM (between 30% and 70%), and average activation of handgrip forces (between 30% and 70%), respectively (Fig. 5).

On average, both MPWO groups demonstrated improvements in handgrip AROM and strength after training, whereas the TOT group showed little or no change. In the Home + Clinic MPWO subgroup, in particular, large gains were observed (see Table 2).

Participants in the TOT group demonstrated a small increase in AROM, while maximum grip strength decreased post-TOT training compared with baseline. This pattern may reflect the clinical phenomenon of tenodesis grasp, in which individuals rely on passive finger flexion during wrist extension to achieve grip. Treating physical therapists monitored participants during all sessions and advised them to avoid compensatory strategies such as tenodesis. As active finger extension improved, reliance on tenodesis may have been reduced, leading to decreased measured grip strength. This suggests that the apparent loss of grip strength was more likely due to reduced compensation than actual loss of function.

On average, participants in the TOT group demonstrated small improvements of 9% in the maximum handgrip AROM and 5.5% in the average activation of the handgrip AROM (between 30% and 70% of the active hand-squeezing cycle), and no improvements in the maximum handgrip force and average activation of the handgrip force (between 30% and 70% of the active hand-squeezing cycle) on the left side. On the right side, there were small improvements of 7% in the maximum handgrip AROM and 15% in the average activation of the handgrip AROM (between 30% and 70% of the active hand-squeezing cycle) and no improvements in the

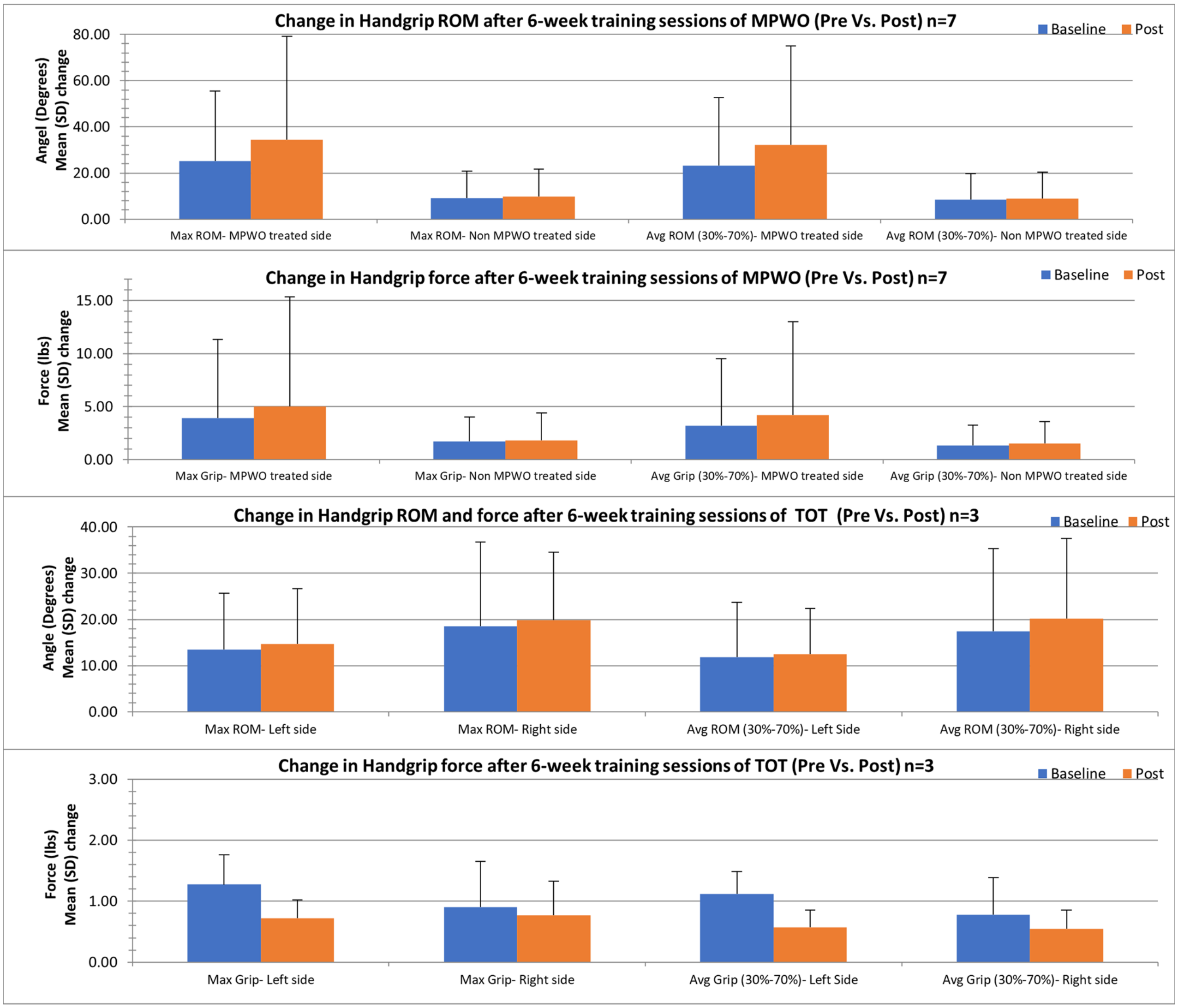

Fig. 5 Data representation of changes in handgrip ROM and forces of participants with SCI ($n = 10$) collected during handgrip squeeze evaluation at baseline and post 6-weeks of training.

maximum handgrip force or in the average activation of the handgrip force (between 30% and 70% of the active hand-squeezing cycle) (Fig. 5).

Between-Group Comparison: An ANCOVA sensitivity analysis adjusting for baseline performance revealed significant differences between groups in the contralateral (non-trained) handgrip strength. For maximum grip force on the non-trained side, Group was significant (F(2,6) = 5.409, $p = 0.045$, partial η^2=0.643). Similarly, for average grip force (30–70% of cycle) on the non-trained side, there was a significant group effect (F(2,6) = 8.289, $p = 0.019$, η^2=0.734). Post-hoc pairwise comparisons indicated that the Home + Clinic MPWO group achieved greater increases in contralateral grip force than the TOT group ($p = 0.021$ for max grip; $p = 0.008$ for avg. grip). The Clinic-only MPWO group's gains in contralateral grip forces were intermediate and not significantly different from TOT ($p > 0.5$). In contrast, no statistically significant group differences were found for outcomes on the trained arm (e.g., trained-side max AROM: F(2,6) = 2.867, $p = 0.134$, η^2=0.489; trained-side max grip: F(2,6) = 0.627, $p = 0.566$). A nonsignificant trend was noted for the trained-side average AROM, (F(2,6) = 4.673, $p = 0.060$, η^2=0.609) suggesting a potential benefit of MPWO over TOT for that measure. Table 2 presents the adjusted post-training means (± SE) for each group and the ANCOVA results for all outcomes.

Effect Sizes: Despite the small sample, the MPWO training produced notable effect sizes. Participants in the combined MPWO group ($n = 7$) had moderate within-group improvements on the trained side for maximum handgrip AROM and average AROM (Cohen's $d \approx 0.30$ for each). The non-trained side showed only small effects ($d < 0.2$ for all measures) in the MPWO group. In the

TOT group, all effect sizes were small (d < 0.2) across outcomes. These findings align with the above statistical results, in that the most substantial gains were observed in the MPWO-trained arm, with the Home + Clinic subgroup achieving the largest improvements, while the control group's changes were negligible (Table 2). The effect size findings, together with the ANCOVA results, suggest that while both MPWO groups benefited from training, the added home practice in the Home + Clinic group may have yielded somewhat greater gains, while the control intervention led to minimal improvements.

Discussion

To our knowledge, this pilot RCT is the first to examine two modes of MPWO use (clinic-only vs. clinic+home) for UE rehabilitation in chronic SCI, compared against standard TOT. After 6 weeks of training, MPWO-assisted therapy was associated with greater improvements in handgrip AROM and strength than TOT in our small sample. In particular, the Home + Clinic MPWO group tended to achieve the largest gains, implying that supplementing supervised sessions with at-home MPWO use may further enhance outcomes.

The substantial improvements observed in the MPWO-trained hand (e.g. large increases in active handgrip ROM and force) likely reflect improved motor control driven by volitional effort combined with repetitive orthotic assistance. Voluntary intention has a known positive influence on motor recovery [22, 23], and the MPWO encourages active participation by amplifying the user's own muscle signals. Interestingly, the contralateral hand in the MPWO groups also showed improvements, despite not being directly trained with the device. This may be explained by the well-known cross-education effect, whereby training one limb can induce functional gains in the opposite limb via neural interhemispheric transfer [24]. Additionally, the cross-training effect observed in the MPWO group may be partially due to increased active engagement of both UEs during functional activities in daily living during the training period, eventually resulting in a possible motor performance improvement on the non-MPWO-trained side. We interpret this finding cautiously and as a potential mechanism rather than a definitive conclusion.Future disseminations will incorporate neurophysiological assessments using surface EMG and electroencephalography (EEG) to better characterize the neural mechanisms and interlimb coupling underlying contralateral effects observed with MPWO training. These tools will allow us to quantify cortical activation patterns and muscle synergy dynamics during bilateral motor tasks, providing mechanistic insight into the neural pathways contributing to cross-education effects.

It is important to consider whether the observed improvements in the clinic-only and Home+Clinic MPWO groups were primarily attributable to the device itself or to the increased total volume of practice. While it is difficult to completely separate these effects, both factors likely contributed. The MPWO facilitates intention-driven, volitional movement by amplifying the user's own residual EMG activity, thereby enhancing active engagement and muscle recruitment. At the same time, the additional home sessions increased the total number of repetitions and practice opportunities, supporting motor learning and neuroplastic adaptation. Future studies will aim to more precisely match overall training volume across groups and employ device-based activity tracking to better isolate the specific contribution of the MPWO assistance from total practice dose.

Although this pilot study focused on motor outcomes (AROM and grip strength), it is important to consider the broader implications for independence in ADL and QOL. Improvements in active handgrip ROM and force may support functional activities such as feeding, grooming, and manipulating objects. However, as no validated ADL or QOL measures were reported, we cannot directly confirm that these motor gains translated into functional or psychosocial improvements. This represents an important gap to be addressed in future investigations.

The small improvements of the TOT group on both trained sides of the UE are limited compared with the results reported in the MPWO group, and others have also noted modest motor gains with adjunctive robotic UE therapy in SCI [20]. Importantly to note that since the treating PTs actively guided participants to avoid tenodesis, the observed decrease in grip strength alongside limited improved AROM should be interpreted as a shift away from compensatory strategies rather than a loss of functional ability. This nuance highlights the importance of considering the quality of motor strategies, not only raw force, in SCI rehabilitation outcomes. Notably, our findings are consistent with other preliminary studies that have reported improved upper limb function after robot-assisted or assist-as-needed training in SCI populations [25–27]. However, like our study, these reports were limited by small sample sizes and heterogeneous methodologies, emphasizing the need for larger controlled trials to confirm efficacy [8, 10]. Overall, findings from this pilot study may provide preliminary evidence supporting MPWO as a possible training orthotic tool in persons with chronic SCI. These findings are particularly exciting considering that MPWO might represent an innovative approach for rehabilitating the highly prevalent and strenuous consequences of UE impairment in SCI patients, which may even be superior to the current TOT.

Limitations

The study's sample size was very small ($n = 10$), so it was likely underpowered to detect all but large effects. We have therefore characterized this work as a pilot study. The limited sample and group imbalances (final groups of 3, 3 and 4 participants) constrain the generalizability of the results. We have acknowledged these issues in the manuscript and emphasized that the findings are preliminary. We also note that our outcome assessors were not blinded to group assignment, which could introduce bias, although participants were not explicitly told which treatment was the "experimental" group. Furthermore, our study assessed outcomes only immediately post-training; we did not evaluate long-term retention of gains. Finally, while we hypothesize that increased voluntary activation contributed to the improvements, EMG or motor unit data to directly confirm changes in neural drive is not included in this pilot study (this is an area for future research). Another limitation is the absence of standardized ADL and QOL outcome measures. While pilot data suggest motor improvements that could be functionally meaningful, without direct ADL/QOL assessments we cannot determine the real-world impact of the intervention.

A larger trial, which includes more participants, a standard of care control, and validated instruments such as the Graded Redefined Assessment of Strength, Sensibility and Prehension (GRASSP) is currently underway and is essential for validating the preliminary findings of this research.

Conclusions

Myoelectric-powered orthoses show promise as assistive training devices for improving hand function in individuals with chronic cervical SCI. In this pilot trial, 6 weeks of MPWO-based training led to greater gains in grip strength and AROM than traditional therapy alone, especially when participants were able to use the device at home in addition to clinic sessions. These results support the feasibility and potential benefits of incorporating wearable myoelectric orthoses into neurorehabilitation. However, given the small sample, these findings should be considered preliminary. An ongoing larger trial will further investigate the efficacy of MPWOs and help determine whether the trends observed here translate into significant functional improvements on a broader scale. If confirmed, home-enabled MPWO programs could represent a valuable advancement in promoting UE recovery and independence in the SCI population.

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Author contributions
GJA: Contributed to the conception, design of the investigation and securing financial support for the study; GJA, AE, SA and SR: Contributed towards data acquisition; GJA, SA, SR, JR, RS, CA, and MW: Processing and analysis of the collected data; GJA: Generated the initial draft of the manuscript; All authors contributed to the interpretation of the data, manuscript writing and revision.

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Data availability
The datasets analyzed and/or code generated during the current study are not publicly available due to the conditions of the funding source, but are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
The study was approved by the Kessler Foundation's Institutional Review Board (IRB), and all the participants signed an Informed Consent form.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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References

1. Center NSCIS. Facts and figures at a glance. Birm AL: Univ Alabama Birm, 2025.
2. Martin R, Silvestri J. Current trends in the management of the upper limb in spinal cord injury. Curr Phys Med Rehabilitation Rep. 2013;1(3):178–86.
3. Hesse S, Schmidt H, Werner C, Bardeleben A. Upper and lower extremity robotic devices for rehabilitation and for studying motor control. Curr Opin Neurol. 2003;16(6):705–10.
4. Maciejasz P, Eschweiler J, Gerlach-Hahn K, Jansen-Troy A, Leonhardt S. A survey on robotic devices for upper limb rehabilitation. J Neuroeng Rehabil. 2014;11(1):3.
5. Fitle KD, Pehlivan AU, O'Malley MK. A robotic exoskeleton for rehabilitation and assessment of the upper limb following incomplete spinal cord injury, in *Robotics and Automation (ICRA)*, 2015 *IEEE International Conference on*, 2015: IEEE, pp. 4960–4966.
6. Frullo JM et al. Effects of assist-as-needed upper extremity robotic therapy after incomplete spinal cord injury: a parallel-group controlled trial. Front Neurorobotics, 11, 2017.
7. Vanmulken D, Spooren A, Bongers H, Seelen H. Robot-assisted task-oriented upper extremity skill training in cervical spinal cord injury: a feasibility study. Spinal Cord. 2015;53(7):547.
8. Ho JS-w, Ko KS-y, Law SW, Man GC-w. The effectiveness of robotic-assisted upper limb rehabilitation to improve upper limb function in patients with cervical spinal cord injuries: a systematic literature review. Front Neurol. 2023;14:1126755.
9. Kim GJ, Rivera L, Stein J. Combined clinic-home approach for upper limb robotic therapy after stroke: a pilot study. Arch Phys Med Rehabil. 2015;96(12):2243–8.
10. Mekki M, Delgado AD, Fry A, Putrino D, Huang V. Robotic rehabilitation and spinal cord injury: a narrative review, *Neurotherapeutics*, vol. 15, no. 3, pp. 604–617, 2018.
11. USA MI. Returning Veterans to Arm Mobility and Independence. [Online]. Available: http://myomo.com/veterans/#veterans-learn-more
12. Ozcan B, et al. Relationship between daily life activities and upper extremity exercise capacity in patients with pulmonary arterial hypertension. Eur Respiratory Soc; 2015.

13. Rudhe C, van Hedel HJ. Upper extremity function in persons with tetraplegia: relationships between strength, capacity, and the spinal cord independence measure. Neurorehabilit Neural Repair. 2009;23(5):413–21.
14. Dunaway S, Dezsi DB, Perkins J, Tran D, Naft J. Case report on the use of a custom myoelectric Elbow–Wrist–Hand orthosis for the remediation of upper extremity paresis and loss of function in chronic stroke. Mil Med, 182, 7, pp. e1963-e1968, 2017.
15. Peters HT, Page SJ, Persch A. Giving them a hand: wearing a myoelectric Elbow-Wrist-Hand orthosis reduces upper extremity impairment in chronic stroke. Arch Phys Med Rehabil, 2017.
16. Willigenburg NW, McNally MP, Hewett TE, Page SJ. Portable myoelectric Brace use increases upper extremity recovery and participation but does not impact kinematics in Chronic, poststroke hemiparesis. J Mot Behav. 2017;49(1):46–54.
17. Cabell M. Poster 217: Case Report on the use of Bilateral Myoelectric Elbow-Wrist-Hand Orthoses for the Remediation of Upper Extremity Paresis following a Spinal Cord Injury, *PM&R*, vol. 9, no. 9, p. S201, 2017.
18. Yozbatiran N, et al. Robotic training and clinical assessment of upper extremity movements after spinal cord injury: a single case report. J Rehabil Med. 2012;44(2):186–8.
19. Osuagwu BA, et al. Home-based rehabilitation using a soft robotic hand glove device leads to improvement in hand function in people with chronic spinal cord injury: a pilot study. J Neuroeng Rehabil. 2020;17(1):40.
20. Jung JH, et al. Effects of combined upper limb robotic therapy in patients with tetraplegic spinal cord injury. Annals Rehabilitation Med. 2019;43(4):445–57.
21. Kirshblum S, Read MS, Rupp R. Classification challenges of the 2019 revised international standards for neurological classification of spinal cord injury (ISNCSCI), *Spinal cord*, vol. 60, no. 1, pp. 11–17, 2022.
22. Jiang C-H, Ranganathan VK, Siemionow V, Yue GH. The level of effort, rather than muscle exercise intensity determines strength gain following a six-week training. Life Sci. 2017;178:30–4.
23. Loy K, et al. Enhanced voluntary exercise improves functional recovery following spinal cord injury by impacting the local neuroglial injury response and supporting the rewiring of supraspinal circuits. J Neurotrauma. 2018;35(24):2904–15.
24. Cirer-Sastre R, Beltrán-Garrido JV, Corbi F. Contralateral effects after unilateral strength training: a meta-analysis comparing training loads. J Sports Sci Med. 2017;16(2):180.
25. Lozano-Berrio V, Alcobendas-Maestro M, Polonio-López B, Gil-Agudo A, de la Peña-González A. Los Reyes-Guzman, the impact of robotic therapy on the Self-Perception of upper limb function in cervical spinal cord injury: A pilot randomized controlled trial. Int J Environ Res Public Health. 2022;19(10):6321. de.
26. Hoffman H, et al. Rehabilitation of hand function after spinal cord injury using a novel handgrip device: a pilot study. J Neuroeng Rehabil. 2017;14(1):22.
27. Singh H, et al. Robot-assisted upper extremity rehabilitation for cervical spinal cord injuries: a systematic scoping review. Disabil Rehabilitation: Assist Technol. 2018;13(7):704–15.

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