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Supplementary information

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Spinal cord stimulation for upper limb motor function in people with chronic post-stroke hemiparesis: a feasibility trial

In the format provided by the authors and unedited

METHODS

Surgical Procedure

Each participant was implanted with two electrode leads in the cervical spinal cord epidural space using a percutaneous surgical approach, and then externalized via a small incision on the back. General anesthesia was induced using propofol and maintained using total intravenous anesthesia (TIVA) at levels that allowed for reliable somatosensory evoked potential monitoring. To facilitate intraoperative monitoring of SCS-evoked electromyographic (EMG) responses, short-acting paralytic was administered only during intubation. Participants were positioned prone and secured using a 3-pin Mayfield head holder. The back and neck were then prepped and draped in a standard sterile fashion. Prophylactic antibiotics were administered. A small incision over the T1-T2 laminas was performed to expose the fascia. A pair of clinically approved 8-contact percutaneous spinal leads (PN 977A260, Medtronic) were placed through a Tuohy needle inserted into the T1-T2 epidural interspace. The rostral lead was inserted first. The rostral lead was steered in situ along the lateral aspect of the spinal cord, such that the most distal contact was positioned at the base of the C3 vertebral process. The caudal lead was placed to span the lower cervical spinal levels down to the T1 vertebral process, overlapping partially with the rostral lead (**Extended Data Fig. 1**). Note that a single 8-contact lead (~52 mm) is insufficient to cover the entire cervical enlargement. Therefore, we used two leads with a small overlap (2–3 contacts) as a safeguard to maintain full coverage in the event of rostro-caudal or medio-lateral migration. Importantly, after an adverse event in participant SCS04—in which stimulation at more rostral spinal levels produced shortness of breath, likely due to unintended activation of the phrenic nerve—we modified our protocol to avoid stimulation of contacts rostral to C4. While a single 8-contact lead could potentially cover C4/C5 to T1 spinal levels, this approach would increase the risk of incomplete cervical coverage in the event of rostro-caudal lead migration. For this reason, we continued implanting two leads in participants SCS05, SCS07, and SCS08, using intraoperative fluoroscopy to identify contacts to avoid.

We positioned both leads lateral to the hemiparetic side of each participant to selectively target dorsal roots innervating only muscles of the affected limb, thus avoiding activation of muscles in the non-affected limb. Fluoroscopy was used to guide lead positioning. However, as fluoroscopy alone can create a distorted impression of the position of the leads due to its planar perspective, we also used electrophysiological recordings to ensure their correct placement. An intraoperative neuromonitoring system (Xltek Protektor, Natus Medical) was used to deliver stimulation and record evoked

EMG responses bilaterally in both arms. We first tested the lateralization of the leads by delivering single-pulse SCS (1-2 Hz) using a few representative contacts (typically 1 at each end and 1 in the middle), while gradually increasing stimulation amplitude. When evoked responses were observed only in paretic-side muscles, but not in the non-affected side, we confirmed proper lateralized lead placement. We then applied high-frequency stimulation (20 Hz) to confirm dorsal root activation; suppression of SCS evoked responses at amplitudes above the motor threshold indicated dorsal, rather than ventral, root activation.

After each lead was placed, the Tuohy needle was removed. The proximal ends of the leads were sutured to the fascia to prevent migration, particularly along the rostro-caudal and medio-lateral axis (Finney, J. N. et al., Frontiers in Surgery, 2025). The distal ends were tunneled subcutaneously and brought out through a separate stab incision over the ipsilateral flank. Both incisions were closed, leaving the externalized portion of the leads covered.

The leads were explanted four weeks after implantation. Participants underwent a preparation procedure similar to the implantation surgery. The cervical incision at the upper thoracic region was reopened to access the leads, which were cut and removed. The distal ends were removed through the lateral incision. Both cervical and lateral incisions were then closed.

Post-operative care

To reduce the risk of infection during the 4-week implantation period, participants were instructed to avoid submerging the implant site in water, with sponge cleaning and gentle rinsing recommended. A water-seal bandage was applied over the lead exit site, and dressings were changed weekly or sooner if peeling occurred. Externalized lead tips were protected with plastic tubes, which were removed only during experimental sessions when connected to the stimulator system.

Custom Stimulation System

A custom stimulation controller was used to deliver SCS during experimental sessions. This custom stimulation system interfaced the externalized lead ends with a single channel, current controlled stimulator (DS8R, Digitimer) connected to a 1-to-8 channel multiplexer (D188, Digitimer). Specifically, the electrode leads were connected via a multi-lead trailing cable (model no. 355531, Medtronic) and a custom input adapter to our stimulation system. A programmed microcontroller board (Arduino Due, Arduino), controlled through a custom-built graphical user interface (GUI) developed in MATLAB,

was used to configure the stimulation amplitude and frequency delivered at each contact electrode. The microcontroller board triggered each stimulus with a digital pulse with amplitude between 0-3.3 V. The firmware of the microcontroller board enabled semi-synchronous stimulation in multiple channels by rapidly switching the output channel after each pulse (time between pulses in different channels was 2.2 ms). Stimulation pulses had cathodic-first, biphasic, symmetric and square waveforms with 200 us to 400 us pulse width and 10 us to 50 us interphase interval. For monopolar stimulation, we used a return electrode placed over the iliac crest contralateral to the impaired arm, whereas we connected two contacts for bipolar stimulation (one as cathode and one as anode).

The GUI sent command packets comprising the packet length, a 1-byte command, and 6 bytes of data. Commands included triggering or stopping stimulation, clearing or saving configurations, reading or writing parameters, and initializing communication. For writing and reading parameters, the command included the parameter, the channel (if applicable), and the value. Each command was followed by a response packet from the microcontroller, which echoed the command, included any requested data, and a status byte indicating whether execution was successful. See **Supplementary Fig. 8** for a schematic of the custom stimulation system. Additional technical details about the custom stimulation controller are available in Powell et al., 2023.

Overflow movements

Overflow movements are unintended and involuntary movements of body parts not involved in the execution of a specific task. To quantify overflow during the reach-and-pull task (see Methods, "**Arm kinematics during reach-and-pull task"**), we quantified the movement of the arm contralateral to the one performing the task (i.e., the less impaired arm). For each reach and pull trial, we fitted a confidence ellipse encompassing 80% of the contralateral arm movement. We then compared the areas of these ellipses between SCS ON and OFF conditions.

Figure Generation

All figures were composed in Adobe Illustrator CC v29.0-29.3.1.

TABLES

Supplementary Table 1. Description of all primary and secondary outcome measures of the clinical trial (clinicaltrials.gov ID NCT04512690). The last column indicates which outcome measures were assessed in this study.

Outcome Measure	Measure Description	Assessed in Study
	primary outcome: safety of epidural cervical spinal cord stimulation (SCS)	
Adverse Events	Study is considered successful if no serious adverse events related to the use of electrical stimulation are reported	Yes
Discomfort and Pain	We will assess the relative level of discomfort and/or pain that is associated with the delivery of stimulation to the spinal cord. After each stimulation train, patients will be asked to report their perceived discomfort level using a 10 value subjective scale. Low values will be assigned to low discomfort, and high values to high discomfort.The study is considered successful if 70% of recruited subjects does not report discomfort or pain at stimulation amplitudes that are required to obtain motor responses in the muscles of the arm and hand.	Yes
	secondary outcomes: upper limb motor function	
Motor Impairment	The Fugl-Meyer Assessment (FMA) is a stroke-specific, performance-based impairment index. It is designed to assess motor functioning, balance, sensation and joint functioning in patients with post-stroke hemiplegia. It is applied clinically and in research to determine disease severity, describe motor recovery, and to plan and assess treatment. The upper extremity motor function score ranges from 0 to 66 points. Minimal Detectable Change (MDC) is 5.2 points. The MCID (Minimally Clinically Important Difference) is 4.25 to 7.25.	Yes
Dexterity / Function: Action Research Arm Test	The investigators will use the Action Research Arm Test (ARAT) assessment to quantify functional hand and arm dexterity. Performances will be compared with SCS-on against SCS-off. The investigators will consider as a minimally acceptable improvement an increase in the affected arm total score of >4 points. Comparison will be done per patient between Stim-on, Stim-off and pre-study baselines. Maximum score on the test is 57 points, minimum score is zero points, with a higher value indicating better dexterity/function.	Yes
Single Joint Force	Isometric torque: measure the isometric torque produced by the subject at the shoulder, elbow and wrist joints. Comparison of SCS-on with SCS-off performance. Success Criteria: ≥20% increased torque production over SCS-off baseline as measured during single-joint isometric torque.	Yes
Joint Velocity	The investigators will use the KINARM robot to quantify joint velocity. The investigators will measure 2D kinematics of the arm during several different horizontal reaching tasks. The investigators will also quantify joint velocity in 3D while subjects perform reach and grasp tasks unsupported. Subjects will be tasked to reach targets or objects and manipulate objects while 3D videos of their arm and hand movements are recorded. Arm and hand kinematics will then be analyzed offline in parallel to EMG analysis of arm and hand muscles. Comparison will be done per patient between Stim-on and Stim-off at different time-points. Given the scientific nature of this task no minimal acceptable improvement is defined and data will be used to understand effects of SCS on arm kinematics.	Yes
Movement Smoothness	The investigators will use the KINARM robot to quantify movement smoothness. The investigators will measure 2D kinematics of the arm during several different horizontal reaching tasks. The investigators will also quantify movement smoothness in 3D while subjects perform reach and grasp tasks unsupported. Subjects will be tasked to reach targets or objects and manipulate objects while 3D videos of their arm and hand movements are recorded. Arm and hand kinematics will then be analyzed offline in parallel to EMG analysis of arm and hand muscles. Comparison will be done per patient between Stim-on and Stim-off at different time-points. Given the scientific nature of this task no minimal acceptable improvement is defined and data will be used to understand effects of SCS on arm kinematics.	Yes
Time to Target	The investigators will use the KINARM robot to quantify time to target. The investigators will measure 2D kinematics of the arm during several different horizontal reaching tasks. The investigators will also quantify time to target in 3D while subjects perform reach and grasp tasks unsupported. Subjects will be tasked to reach targets or objects and manipulate objects while 3D videos of their arm and hand movements are recorded. Arm and hand kinematics will then be analyzed offline in parallel to EMG analysis of arm and hand muscles. Comparison will be done per patient between Stim-on and Stim-off	Yes

Outcome Measure	Measure Description	Assessed in Study
	at different time-points. Given the scientific nature of this task no minimal acceptable improvement is defined and data will be used to understand effects of SCS on arm kinematics.	
Spasticity	The investigators will quantify spasticity scores using the Modified Ashworth Scale (MAS) for the shoulder, elbow and wrist joint and compare values with SCS-on and SCS-off. The investigators will consider as a minimally acceptable improvement a decrease of MAS >1, if available for the specific joint. Comparison will be done per patient between Stim-on and Stim-off and pre-study baselines. Maximum score on the MAS is 4, minimum score is 0, with a lower number indicating less spasticity.	Yes
Cortico-spinal Tract Integrity	The investigators will measure muscle evoked potential consequent to Transcranial Magnetic Stimulation of the cortico-spinal tract to assess integrity of the cortico-spinal tract. They will also explore SCS responses when conditioned by a TMS pulse and vice-versa.	Yes
Sensorimotor Network Structure Integrity	The investigators will perform High-definition Diffusion Weighted Imaging to quantify Fractional Anisotropy as a measurement of axon integrity in the brain and spinal cord pre and post study.	Yes
Sensory motor integration: success-rate	The investigators will use the KINARM robot to quantify functional sensory acuity and sensory-motor integration. The investigators will measure 2D kinematics of the arm during different exercises where subjects will reach to defined targets with and without visual feedback. These tasks are designed to assess proprioception acuity and sensory-motor integration. Success-rate will be quantified offline. Comparison will be done per patient between Stim-on and Stim-off at different timepoints. Given the scientific nature of this task no minimal acceptable improvement is defined and data will be used to understand effects of SCS on sensorimotor integration processes.	No
Sensory motor integration: displacement error	The investigators will use the KINARM robot to quantify functional sensory acuity and sensory-motor integration. The investigators will measure 2D kinematics of the arm during different exercises where subjects will reach to defined targets with and without visual feedback. These tasks are designed to assess proprioception acuity and sensory-motor integration. Displacement error from the true target location will be quantified offline. Comparison will be done per patient between Stim-on and Stim-off at different timepoints. Given the scientific nature of this task no minimal acceptable improvement is defined and data will be used to understand effects of SCS on sensorimotor integration processes.	No
Sensorimotor Network Function	The investigators will perform resting state and motor-task functional MRI of the brain and spinal cord to quantify neural network activation at rest and during the execution of simple motor tasks.	No
Spinal Circuit Excitability	The investigators will measure H-reflexes of arm muscles obtained during stimulation of the peripheral nerves to quantify excitability of spinal motoneurons to stimulation of primary sensory afferents pre and post-study. Expected Result: The main scientific hypothesis is that SCS will change sensori-to-motoneuron excitability that can be measured via H-reflex responses pre and post-implant.	No
Motoneuron Firing Rates	The investigators will use high-density EMGs on arm muscles to calculate firing rates of single spinal motoneuron discharge during isometric maximal voluntary contractions.	No

Supplementary Table 2. Time, in hours, engaged in active movement under spinal cord stimulation (SCS) ON and OFF conditions, across participants and time points.

Time on active movement (SCS OFF/SCS ON)								
Time point	**SCS01**	**SCS02**	**SCS03**	**SCS04**	**SCS05**	**SCS07**	**SCS08**	**AVERAGE**
Pre-implant	0.9/0	0/0	0.3/0	0.7/0	3.6/0	1.6/0	3.1/0	**1.5/0**
SCS intervention (post-implant)								
Week 1	0.4/0.7	0.3/0.5	1.0/0.9	0.6/1.1	0.6/1.6	0.9/1.1	0.7/2.1	**0.6/1.1**
Week 2	0.3/0.8	0.4/0.6	0.4/1.0	0.6/1.3	1.5/2.1	1.2/1.5	1.2/2.3	**0.8/1.4**
Week 3	0.7/1.5	0.4/1.0	0.6/0.8	0.5/1.1	1.7/2.7	1.0/1.8	1.2/2.8	**0.9/1.7**
Week 4	0.4/0.4	0.6/1.0	0.5/0.9	0.8/1.3	1.2/2.0	0.7/1.3	1.1/2.2	**0.8/1.3**
TOTAL (SCS intervention)	1.8/3.4	1.7/3.1	2.5/3.6	2.5/4.8	5.0/8.4	3.8/5.7	4.2/9.4	**3.1/5.5**

Supplementary Table 3. Fugl-Meyer Assessment (FMA) scores for upper-extremity motor function under spinal cord stimulation (SCS) ON and OFF conditions, across participants and time points. Total scores and subcomponent scores are reported.

Fugl-Meyer Assessment (FMA) for upper-extremity motor function								
Time point	**SCS01**	**SCS02**	**SCS03**	**SCS04**	**SCS05**	**SCS07**	**SCS08**	**TOTAL**
PRE-IMPLANT (BASELINE)								
Reflexes	4	4	4	4	4	4	4	4
Flexor Synergy (FS)	8	5	6	6	6	7	9	12
Extensor Synergy (ES)	4	2	6	5	5	3	5	6
Movement Combining Synergy (MCS)	3	0	3	2	0	2	3	6
Movement Out-of-Synergy (MOS)	1	0	1	0	1	0	1	6
Normal Reflex Activity	0	0	0	0	0	0	0	2
Wrist (WRIST)	3	0	2	0	0	3	4	10
Hand (HAND)	9	0	2	2	2	11	2	14
Coordination/Speed	4	4	4	4	2	4	4	6
TOTAL	36	15	28	23	20	34	32	66
WEEK 2 (SCS OFF/SCS ON)								
Reflexes	4/4	4/4	4/4	4/4	4/4	4/4	4/4	4/4
Flexor Synergy (FS)	8/10	7/7	8/8	6/6	5/8	7/8	10/10	12/12
Extensor Synergy (ES)	5/5	3/3	6/6	4/6	5/5	3/4	6/6	6/6
Movement Combining Synergy (MCS)	3/5	0/0	2/3	0/3	1/1	1/3	3/3	6/6
Movement Out-of-Synergy (MOS)	1/2	0/0	1/1	1/2	1/1	0/1	1/2	6/6
Normal Reflex Activity	0/0	0/0	0/0	0/0	0/0	0/0	0/0	2/2
Wrist (WRIST)	3/7	0/0	2/5	1/1	2/2	2/2	5/5	10/10
Hand (HAND)	7/11	0/0	2/2	1/2	3/3	11/10	3/3	14/14
Coordination/Speed	4/4	4/4	4/4	4/4	3/3	4/4	4/4	6/6
TOTAL	35/48	18/18	29/33	21/28	24/27	32/36	36/37	66/66
WEEK 4 (SCS OFF/SCS ON)								
Reflexes	4/4	4/4	4/4	4/4	4/4	4/4	4/4	4/4
Flexor Synergy (FS)	10/11	6/6	11/11	6/6	8/7	8/9	10/10	12/12
Extensor Synergy (ES)	6/6	3/3	6/6	6/6	5/5	3/4	6/6	6/6
Movement Combining Synergy (MCS)	5/5	0/0	3/4	1/2	1/1	3/3	4/4	6/6
Movement Out-of-Synergy (MOS)	2/4	0/0	1/1	0/2	1/1	1/1	2/2	6/6
Normal Reflex Activity	0/0	0/0	0/0	0/0	0/0	0/0	0/0	2/2
Wrist (WRIST)	5/6	0/0	4/3	0/1	5/5	2/2	4/4	10/10
Hand (HAND)	11/11	1/0	2/4	2/1	3/3	10/10	2/3	14/14
Coordination/Speed	4/4	4/4	4/4	4/4	3/3	4/4	4/4	6/6
TOTAL	47/51	18/17	35/37	23/26	30/29	35/37	36/37	66/66
FOLLOW-UP								
Reflexes	4	4	4	-	4	4	4	4
Flexor Synergy (FS)	9	6	9	-	7	7	10	12
Extensor Synergy (ES)	6	2	6	-	6	5	6	6
Movement Combining Synergy (MCS)	3	0	3	-	1	3	4	6
Movement Out-of-Synergy (MOS)	4	0	1	-	1	0	1	6
Normal Reflex Activity	0	0	0	-	0	0	0	2
Wrist (WRIST)	5	0	2	-	5	3	4	10
Hand (HAND)	11	1	2	-	2	10	3	14
Coordination/Speed	4	4	4	-	2	4	4	6
TOTAL	46	17	31	-	28	36	36	66

Supplementary Table 4. Fugl-Meyer Assessment (FMA) scores for upper-extremity sensory function under spinal cord stimulation (SCS) ON and OFF conditions, across participants and time points. Total scores and subcomponent scores are reported.

Fugl-Meyer Assessment (FMA) for upper-extremity sensory function								
Time point	**SCS01**	**SCS02**	**SCS03**	**SCS04**	**SCS05**	**SCS07**	**SCS08**	**TOTAL**
PRE-IMPLANT (BASELINE)								
Light Touch	4	2	2	1	3	4	4	4
Proprioception	7	0	6	2	6	7	8	8
TOTAL	11	2	8	3	9	11	12	12
WEEK 2 (SCS OFF/SCS ON)								
Light Touch	4/4	1/1	2/2	1/1	3/3	3/3	4/4	4/4
Proprioception	5/5	0/0	3/3	2/0	6/7	6/7	8/8	8/8
TOTAL	9/9	1/1	5/5	3/1	9/10	9/10	12/12	12/12
WEEK 4 (SCS OFF/SCS ON)								
Light Touch	4/4	1/1	2/2	2/0	3/3	4/3	4/4	4/4
Proprioception	7/7	0/0	5/5	2/1	6/6	8/8	8/8	8/8
TOTAL	11/11	1/1	7/7	4/1	9/9	12/11	12/12	12/12
FOLLOW-UP								
Light Touch	4	2	2	-	3	4	4	4
Proprioception	7	0	4	-	6	8	8	8
TOTAL	11	2	6	-	9	12	12	12

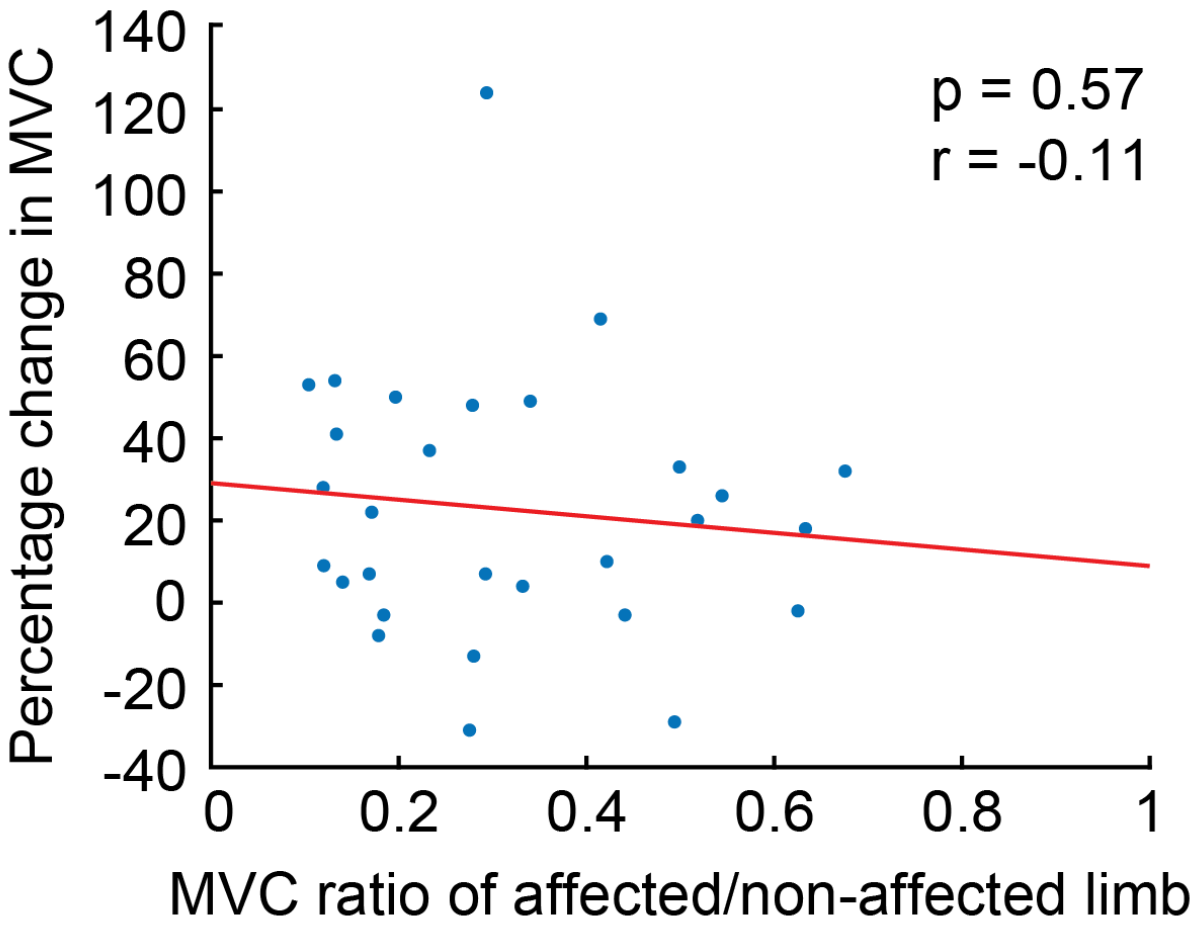
Supplementary Table 5. Action Research Arm Test (ARAT) scores under spinal cord stimulation (SCS) ON and OFF conditions, across participants and time points. Total scores and subcomponent scores are reported.

Action Research Arm Test (ARAT)								
Time point	**SCS01**	**SCS02**	**SCS03**	**SCS04**	**SCS05**	**SCS07**	**SCS08**	**TOTAL**
PRE-IMPLANT (Affected/Non-affected arm)								
Grasp	15/18	0/18	0/18	0/18	0/18	4/18	1/18	18/18
Grip	8/12	0/11	2/12	1/11	2/12	3/11	2/12	12/12
Pinch	0/18	0/18	0/15	0/15	0/14	2/18	0/17	18/18
Gross Movement	8/9	3/9	0/9	5/9	3/9	5/9	5/9	9/9
TOTAL	31/57	3/56	2/54	6/53	5/53	14/56	8/56	57/57
WEEK 4 - SCS OFF (Affected/Non-affected arm)								
Grasp	13/18	-	0/18	0/-	3/18	4/18	1/18	18/18
Grip	8/12	-	2/12	1/-	4/12	3/12	2/12	12/12
Pinch	8/18	-	1/15	0/-	0/16	0/16	0/18	18/18
Gross Movement	7/9	-	7/9	5/-	3/9	5/9	5/9	9/9
TOTAL	36/57	-	10/54	6/-	10/55	12/55	8/57	57/57
WEEK 4 - SCS ON (Affected/Non-affected arm)								
Grasp	18/18	-	0/18	2/-	3/18	4/18	1/18	18/18
Grip	8/12	-	5/12	1/-	4/12	2/11	2/12	12/12
Pinch	12/18	-	1/15	0/-	0/16	0/13	0/18	18/18
Gross Movement	7/9	-	7/9	5/-	3/9	5/9	5/9	9/9
TOTAL	45/57	-	13/54	8/-	10/55	11/51	8/57	57/57
FOLLOW-UP (Affected/Non-affected arm)								
Grasp	16/18	0/18	5/18	-	0/18	4/18	1/18	18/18
Grip	8/12	0/10	0/12	-	0/12	3/12	3/12	12/12
Pinch	0/17	0/18	0/15	-	0/14	0/16	0/18	18/18
Gross Movement	8/9	3/9	4/7	-	3/9	5/9	5/9	9/9
TOTAL	32/56	3/55	9/52	-	3/53	12/55	9/57	57/57

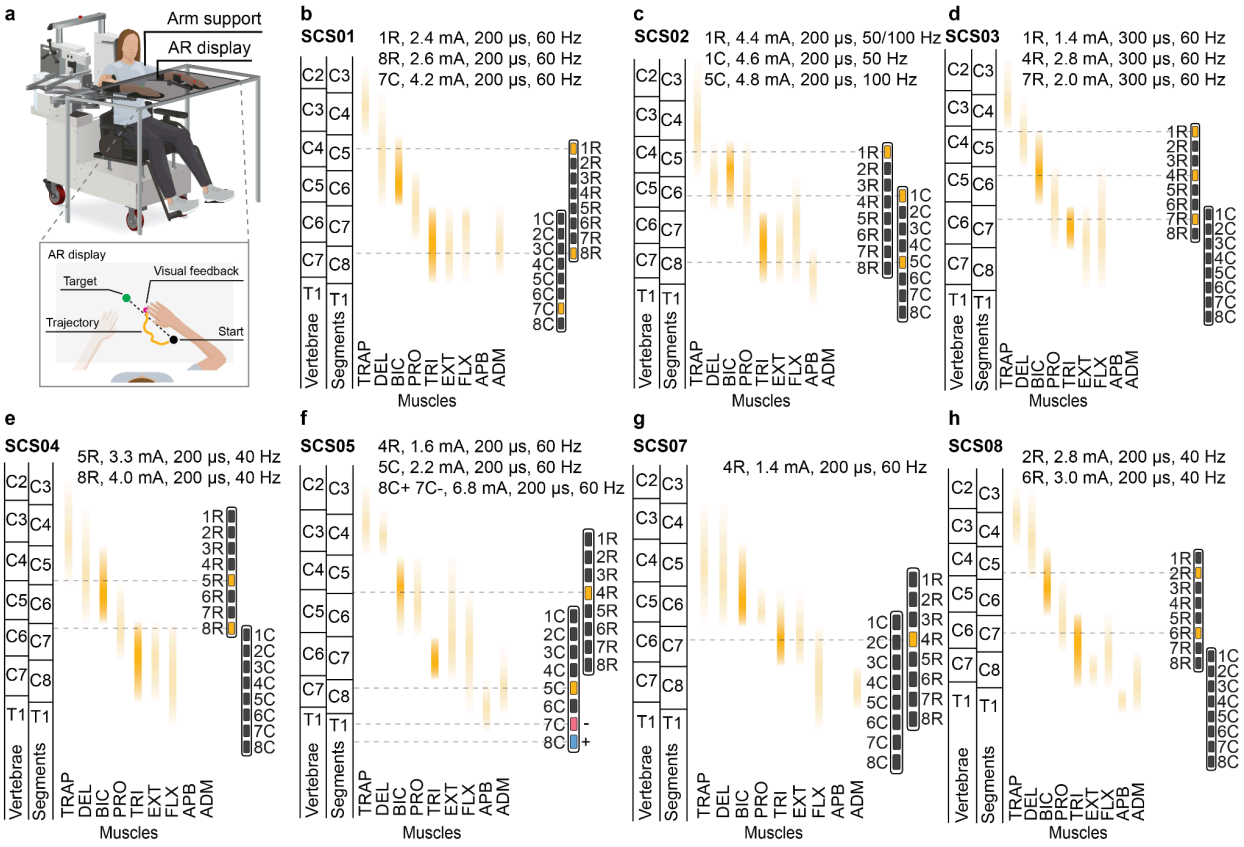
Supplementary Table 6. Linear correlations between agonist–antagonist muscle activation ratios and arm kinematic metrics across stimulation conditions. Myoelectric activity of the triceps brachii (TRI), brachioradialis (BR), and biceps brachii (BIC) muscles was quantified as the root mean square (RMS) of the EMG signal envelope during the reach and pull phases of a planar center-out task. Agonist–antagonist activation ratios (TRI/BR and TRI/BIC) were computed under spinal cord stimulation (SCS) ON and OFF conditions. Pearson correlation coefficients and p-values were calculated to assess the linear correlation between the percentage change in muscle activation ratios (SCS ON/SCS OFF) and average changes in arm kinematic parameters (path efficiency, deviation error, velocity peaks, and log dimensionless jerk). Statistically significant correlations ($p < 0.05$) are highlighted in bold.

TRI/BR (SCS ON/SCS OFF)				
	Reach (n = 24)		**Pull (n = 23)**	
	p-value	Pearson coefficient	p-value	Pearson coefficient
Path efficiency	**<0.001**	**0.644**	0.081	-0.302
Deviation error	0.136	0.234	0.067	-0.322
Velocity peaks	**<0.001**	**0.609**	0.365	-0.076
Log dimensionless jerk	**0.004**	**0.530**	0.186	-0.195
TRI/BIC (SCS ON/SCS OFF)				
	Reach (n = 24)		**Pull (n = 23)**	
	p-value	Pearson coefficient	p-value	Pearson coefficient
Path efficiency	**0.013**	**0.452**	**0.029**	**-0.399**
Deviation error	0.786	0.264	0.202	-0.183
Velocity peaks	**<0.001**	**0.613**	**<0.001**	**-0.649**
Log dimensionless jerk	**0.006**	**0.502**	**<0.001**	**-0.612**

FIGURES

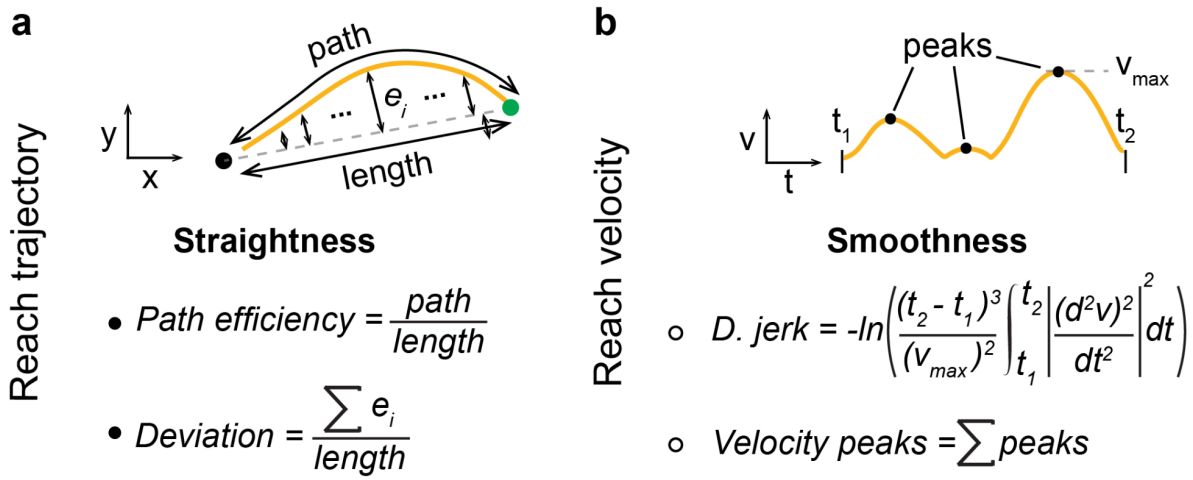


Supplementary Fig. 1 | Correlation between the percentage change in Maximum Voluntary Contraction (MVC) strength under spinal cord stimulation (SCS) conditions and impairment. Isometric MVC during SCS ON and OFF conditions were used to assess strength of shoulder flexion, shoulder extension, elbow flexion, elbow extension and grip for all participants, except SCS02 since the MVC of the non-affected limb was not measured for this participant (n = 30 measurements). Across all isolated movements, the ratio between the MVC force produced by the affected and non-affected limb showed no correlation with the percentage change in MVC strength (r=-0.11; p=0.57).

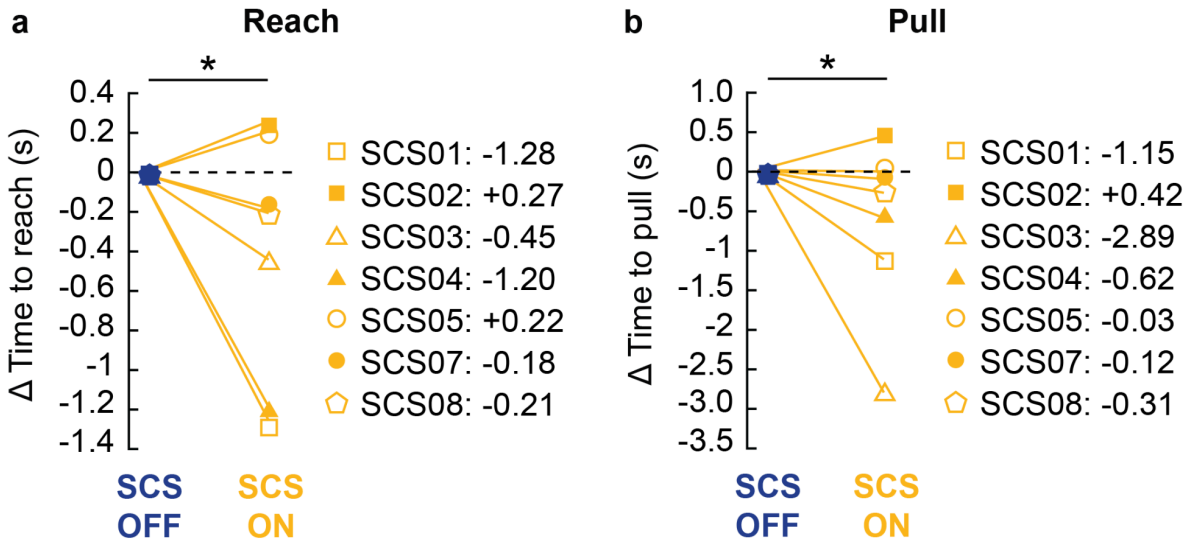


Supplementary Fig. 2 | Spinal segment maps and spinal cord stimulation (SCS) configuration during arm dexterity reach-and-pull task.

a. Experimental setup for reach-and-pull task using an exoskeleton robot (KINARM) for anti-gravity arm support. **b-h.** Spinal segment maps indicating the spinal levels and motor neuron pools targeted by the electrodes used for each participant (SCS01 - SCS08) during the task. The specific electrode configuration for each participant is also provided. Abbreviations: R, contacts in the rostral lead; C, contacts in the caudal lead; TRAP, trapezius; DEL, deltoids; BIC, biceps brachii; PRO, pronator; TRI, triceps brachii; EXT, wrist extensors; FLX, wrist flexors; APB, abductor pollicis brevis; ADM, abductor digiti minimi. The highlighted vertical gradient bars indicate motor pools of the BIC and TRI, while the dashed horizontal lines indicate approximate spinal levels of the contacts for each participant.

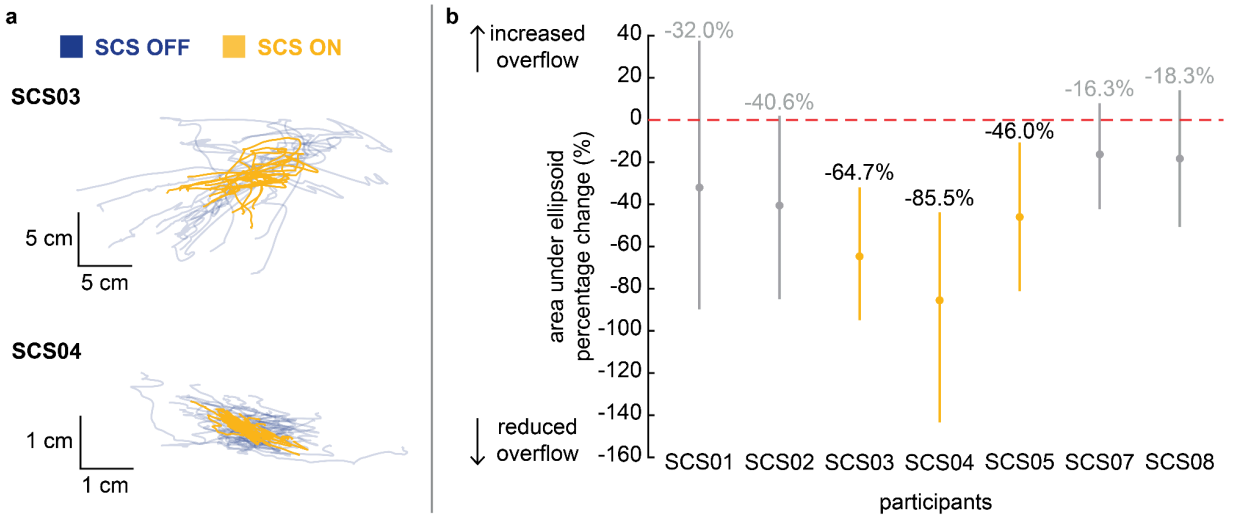


Supplementary Fig. 3 | Arm kinematic metrics.
Reach and pull trajectories were quantified using **a.** straightness metrics (path efficiency ratio and deviation error) and **b.** smoothness metrics (log dimensionless jerk and number of velocity peaks).

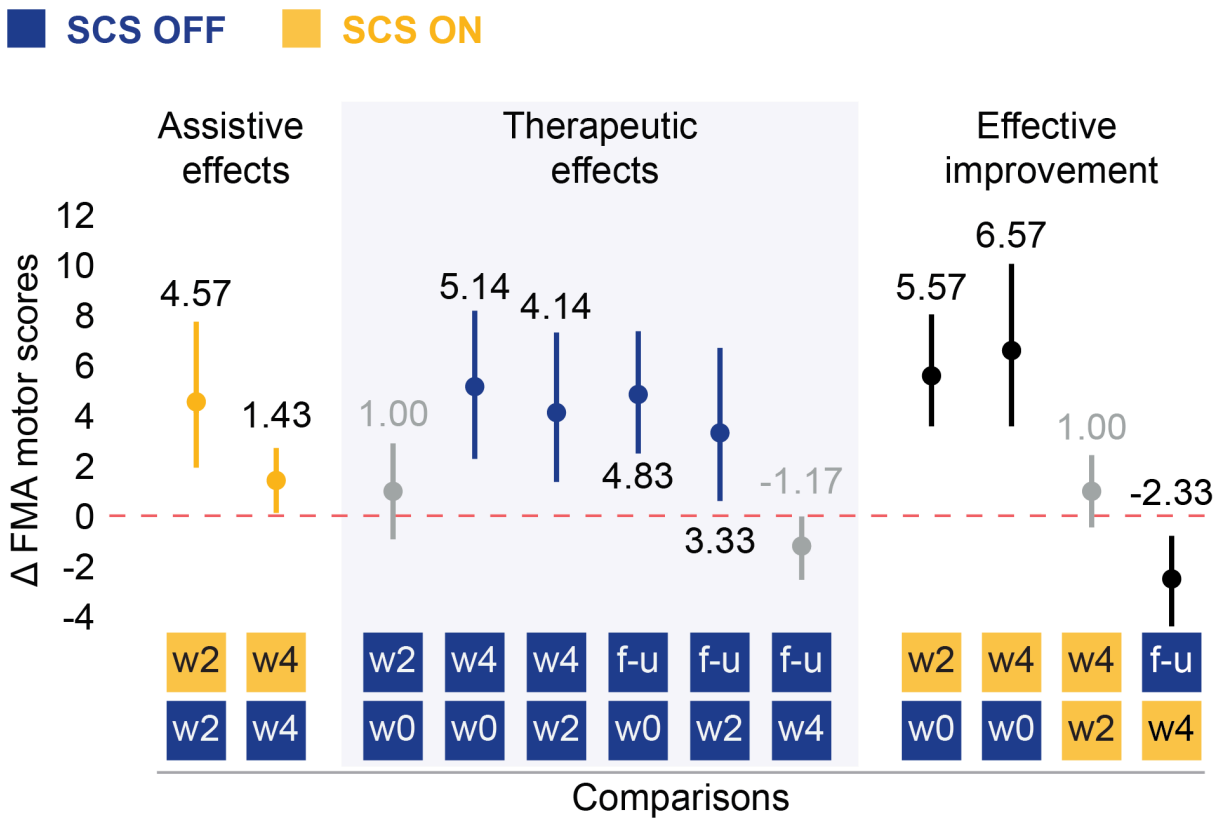


Supplementary Fig. 4 | Change in duration of reach and pull phases under spinal cord stimulation (SCS).

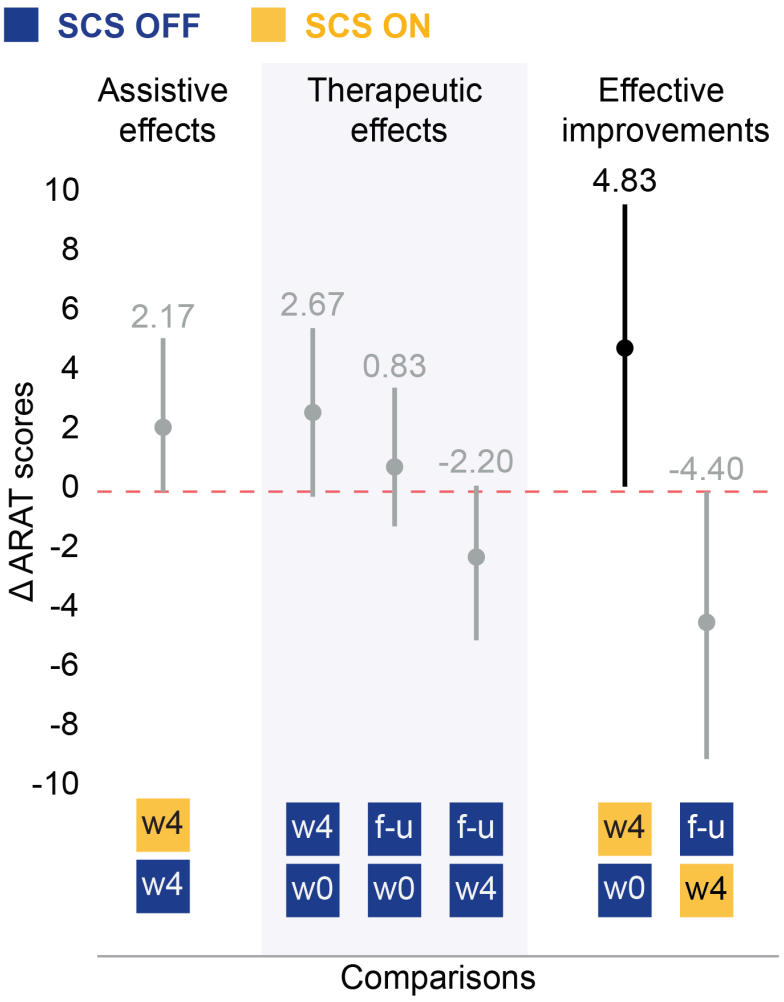
Significant decrease in duration, measured in seconds (s), of **a.** reach (average -0.41s) and **b.** pull (average -0.67s) phases under SCS ON compared to SCS OFF condition across all participants. Movement durations for both SCS ON and OFF conditions were subtracted by the duration of the SCS OFF condition for n=27 trajectories across all participants. Inference on mean differences is performed by bootstrapping the repetitions obtained for each stimulation condition, with n = 10,000 bootstrap samples; the single asterisk indicates statistical significance and rejection of the null hypothesis of no difference with a 95% CI.



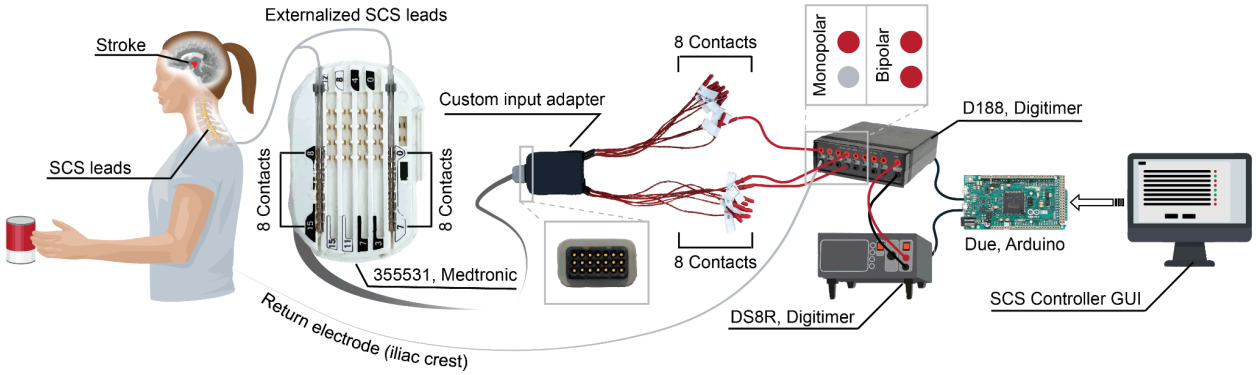
Supplementary Fig. 5 | Overflow movements during the reach-and-pull task.
Assistive effects of spinal cord stimulation (SCS) on overflow movements of the arm contralateral to the one performing the reach-and pull task, i.e., the less affected arm, were quantified. **a.** Representative examples of overflow movements from two participants, SCS03 and SCS04, are shown for SCS OFF (light blue) and SCS ON (yellow) conditions. **b.** The area of the confidence ellipse encompassing 80% of the contralateral arm movements were compared across stimulation conditions. Overflow movements were significantly lower (vertical yellow bars) during the SCS ON condition in 3 out of 7 participants (SCS03, SCS04, and SCS05), but not significantly different (vertical gray bars) for the others. Inference on mean differences is performed by bootstrapping the repetitions obtained for each stimulation condition, with n = 10,000 bootstrap samples. Confidence intervals (95%) of the percentage difference of the ellipsoid area between SCS ON and OFF conditions are shown with vertical traces around the average (circle).



Supplementary Fig. 6 | Average change in the Fugl-Meyer Assessment (FMA) scores for upper-extremity motor function across spinal cord stimulation (SCS) ON and OFF conditions. Assistive effects of SCS were measured as the difference in FMA scores between SCS ON and OFF conditions at week 2 (w2) and week 4 (w4) for n = 7 participants. Therapeutic effects of SCS were measured as the difference in FMA scores between time points (pre-implant, w0; week 2, w2; week 4, w4; follow-up, f-u) under SCS OFF condition for n = 7 participants. Effective improvement was measured as the difference in FMA scores between SCS OFF at pre-implant (w0) for n = 7 participants or follow-up (f-u) for n = 6 participants, and SCS ON at week 2 (w2) or week 4 (w4) for n = 7 participants. Inference on mean differences is performed by bootstrapping the repetitions obtained for each stimulation condition, with n = 10,000 bootstrap samples. Confidence intervals (95%) of the difference in FMA scores between conditions are shown with vertical traces around the average (circle). Vertical traces in yellow, blue, and black indicate significant increases in FMA scores for assistive effects, therapeutic effects, and effective improvement, respectively, whereas gray traces indicate no improvement. SCS OFF conditions are represented in blue boxes, while SCS ON conditions are represented in yellow boxes.



Supplementary Fig. 7 | Average change in the Action Research Arm Test (ARAT) scores for across spinal cord stimulation (SCS) ON and OFF conditions.
Assistive effects of SCS were measured as the difference in ARAT scores between SCS ON and OFF conditions at week 4 (w4) for n=6 participants. Therapeutic effects of SCS were measured as the difference in ARAT scores between time points (pre-implant, w0; week 4, w4; follow-up, f-u) under SCS OFF condition for n=6 participants. Effective improvement was measured as the difference in ARAT scores between SCS OFF at pre-implant (w0) or follow-up (f-u) and SCS ON at week 4 (w4) for n=6 participants. Confidence intervals (95%) of the difference in ARAT scores between conditions are shown with vertical traces around the average (circle). Vertical traces in black indicate significant increases in ARAT scores for effective improvement, whereas gray traces indicate no improvement. SCS OFF conditions are represented in blue boxes, while SCS ON conditions are represented in yellow boxes.



Supplementary Fig. 8 | Schematic of the experimental setup connecting the spinal cord stimulation (SCS) leads to the custom stimulation system.

The SCS leads were externalized through a skin incision and connected to a 16-contact multi-lead trailing cable (Medtronic, 355531). A custom input adapter converted the trailing cable output to touchproof connectors. Current was delivered using a single-channel, current-controlled stimulator (Digitimer DS8R) connected to a 1-to-8 channel multiplexer (Digitimer D188). A programmed microcontroller board (Arduino Due, Arduino) controlled stimulation amplitude and frequency via a custom-built graphical user interface (GUI). The microcontroller also selected multiplexer channels and triggered stimulation with precise timing. Biphasic square current pulses were delivered with the first polarity as negative. Monopolar stimulation was performed using a surface electrode placed over the iliac crest contralateral to the leads, or a distant contact on the lead (e.g., 1R as anode and 8R as cathode), as anode (return electrode). Bipolar stimulation was delivered using a pair of close contacts, one connected as cathode and another as anode.