Expanding Functional Workspace for People With C5-C7 Spinal Cord Injury With Supernumerary Dorsal Grasping

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***Abstract*—Spinal cord injuries (SCI) substantially affect sensory, motor, and autonomous functions below the level of injury, reducing the independence and quality of life for affected individuals. Specifically, people with SCI between C5 and C7 cervical levels encounter limitations in voluntary finger and wrist flexion, reducing grasp capability. Compensatory strategies like tenodesis grasp, whereby wrist extension passively closes the fingers, remain; this is effective for small and light objects but insufficient for heavier ones. Typically, wearable assistive exoskeletons are designed to actuate a person's fingers, however, such devices are sensitive to anatomical variability, such as hand size and joint contractures. The *Dorsal Grasper* is a wearable device designed to address this challenge by leveraging voluntary wrist extension and providing human-robot collaborative grasping capabilities with underactuated supernumerary fingers on the back of the hand. In this study, we introduce kinematic assessment methods that we use to show how the *Dorsal Grasper* expands the graspable workspace and reduces trunk motion, especially in situations where the use of a wheelchair restricts the individual's posture. Our functionally relevant experiments with multiple SCI participants demonstrate the *Dorsal Grasper*'s potential as a versatile assistive solution for enhancing grasping capability in individuals with distinct SCI profiles.**

***Index Terms*—Wearable robotics, physically assistive devices, human-robot collaboration.**

I. INTRODUCTION

SPINAL cord injury (SCI) causes dysfunction of the body's sensory, motor, and autonomic systems below the level of injury [1]. This generates challenges for the individual and their care providers due to reduced function, high cost of treatment, and prolonged recovery period [2]. Individuals with SCI also often endure a concurrent impact on their psychological and social well-being, as well as an overall decrease in quality of life [3]. According to estimates, there are between 10.4 and 83 cases per million people every year [4], and the incidence of SCI is gradually increasing [2].

The most common category of SCI is at the cervical level, causing tetraplegia [5]. People with SCI between C5 and C7 cervical levels generally lose the ability to voluntarily flex their fingers and wrist, thus reducing grasp function [6]. Studies of individuals with cervical level SCI found they believed restoring arm and hand function would considerably enhance their quality of life; they scored hand and arm function above all other functions (e.g., walking, bowel/bladder control, etc.) as the primary research priority [7], [8].

People with SCI below C5 are commonly able to actively extend their wrist (extensor carpi radialis longus and brevis), which, fortunately, can elicit passive thumb-to-forefinger motion for lateral gripping and finger-to-palm flexion for whole hand gripping due to shortening of the muscles (flexor pollicis longus, flexor digitorium superficialis and profundus) [6]. This compensatory hand skill is called "tenodesis grasp," as demonstrated in Fig. 1(a). Tenodesis grasp allows for picking up light and small objects, however it is less suitable for heavier and larger ones [9]. In addition, compensatory strategies like tenodesis grasp may lead to overuse injury [10] and limit the reachable workspace [11]. For heavier and larger objects, bimanual manipulation is often used, however, this limits the workspace even further. A limited workspace may lead to increased body compensation, posing challenges for tetraplegic individuals whose body motion and orientation are constrained by their kinematic limitations and the use of essential tools, such as a wheelchair. Thus, rehabilitative and assistive interventions that re-enable grasp function while expanding workspace may improve overall daily function.

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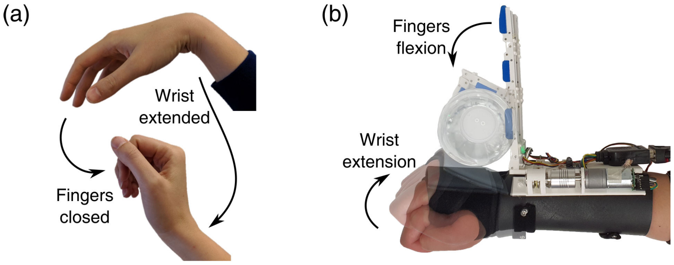

Fig. 1. (a) Demonstration of tenodesis finger motion from [12] by a person without spinal cord injury. Active wrist extension causes passive finger flexion. (b) The *Dorsal Grasper* includes a set of underactuated fingers and an artificial palm on the back of the hand. Here, a water-bottle is grasped using both active wrist extension and supernumerary finger flexion.

A. Background: Re-Enabling Grasp Function

Several methods have been proposed to restore lost grasping function in the SCI population. Functional electrical stimulation (FES) [13] is a non-invasive method that artificially stimulates peripheral nerves to restore contraction of the paralyzed muscle [14]. However, FES faces several ongoing challenges, such as skin discomfort [15], low muscle selectivity [16], and muscle fatigue [17]. More invasive approaches have included nerve transfer [18] and tendon transfer [19]. Although these surgeries have shown positive results, they are nonetheless underutilized [20], [21]. On the other hand, wearable assistive orthotics provide a practical non-invasive pathway to improve daily function [22] as well as enabling rapid prototyping for early studies on normative populations [23].

Over the past several years, various wearable devices for the upper extremities have been developed, reviewed in [24], [25], and [26]. Rigid exoskeletons benefit from a precise analysis of power transmission to various joints. One common device is the wrist-driven orthosis (WDO) with a mechanical linkage to enhance tenodesis grasping [11], [12]. However, difficulties associated with these devices include comfort and fitting to different individuals [27], [28]. Thus, SCI patients frequently abandon these devices over time as they get accustomed to doing tenodesis without assistance and instead choose to utilize a set of more specialized instruments [29]. Soft devices with compliant, lightweight structures provide more comfort and adaptability. Recent soft wearable research aims at developing soft actuators, such as fabric-based actuators [30], [31] and elastomeric chambers [32], [33]. Others develop interfaces taking advantage of compliant properties. Soft-linkage or hybrid devices [34], [35], [36] are relatively easy to align with humans anatomy, enabling users to wear them for long periods in various environments [37], [38]. All of these devices – rigid or soft – actuate or support the person's fingers to enable prehensile gripping. Nonetheless, all of these approaches have their drawbacks. Instead of harnessing the user's body power, they may unintentionally restrict it. Additionally, they have the potential to constrain the wearer's remaining dexterity and present challenges in adapting to individuals with substantial anatomical variations in their joints.

Supernumerary devices offer another solution, where the user/device is not required to actuate the person's fingers [39]. One such device, developed for stroke survivors and other patients with limb impairment, included supernumerary robotic fingers mounted on a wrist brace that oppose the palm [40]. Another device applied to chronic stroke patients consisted of a soft-sixth finger that opposed the hand's radial side for grasp compensation [41]. Prior work proposes that supernumerary grasping with the back of the hand may be helpful for people with C5-C7 SCI who retain voluntary wrist extension but limited or no finger function. A preliminary version of the device, hereby referred to as the *Dorsal Grasper*, was first presented in [42]. This dorsal format works independently of the finger state, such that users' fingers can be either soft or stiff and passively either open or close due to variability in muscle stiffness and contractures [27], [43], as well as changes in daily activity. Such dorsal grasping would mimic power palmar grasping, and could therefore replace bimanual grasping for heavier and larger objects. This prior work suggests the *Dorsal Grasper* could thereby expand the reachable workspace. Additionally, the user should be able to continue utilizing residual dexterity while wearing the device, as this format doesn't constrain the fingers or hand. However, these intentions regarding the potential capabilities associated with the *Dorsal Grasper* were not previously tested. To address this knowledge gap, we now study the whether a revised supernumerary *Dorsal Grasper* can expand the range of graspable objects and workspace while mitigating exertion. We also test whether wearing the device impedes other compensatory grasp strategies already useful for people with SCI.

B. Overview

In the present work, we perform a design iteration and analysis of device performance related to functional workspace. Notably, we expand on the subject population to include multiple SCI participants. Analysis is expanded to include both quantitative kinematic performance across different device conditions in a newly designed experimental setup for functional workspace, as well as post hoc qualitative device perception that includes device usage with real-world objects. The contributions of this study are summarized as follows:

1) Introduction of an updated *Dorsal Grasper* that integrates a bending sensor to provide a new control method, leveraging the inherent wrist extension capability of SCI subjects.
2) Measurement of each participant's graspable workspace using various grasping methods, comparing unimanual and bimanual grasping without the device, as well as with the device employing two distinct control modes.
3) Kinematic analysis of the functional workspace and body compensation in a controlled setup, simulating a wheelchair-inaccessible environment.
4) Qualitative evaluation of device perception through contextual inquiry with the targeted population.

In Section II, we present the implementation and performance characterization of the updated *Dorsal Grasper* (Fig. 1(b)). Then, in Section III, we describe the experimental methods used to measure body kinematics during reach-to-grasp trials in human subjects, both with and without SCI. Experimental results presented in Section IV include both qualitative and quantitative device assessments. Observations

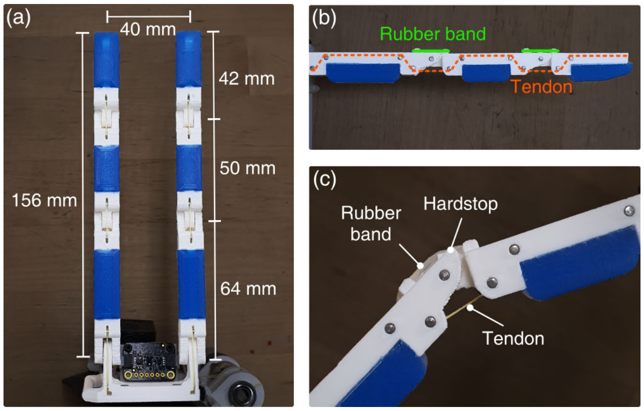

Fig. 2. Tendon driven fingers. (a) Two three-phalanx fingers in a parallel position. (b) Tendon routing (orange) and rubber band (green). (c) Proximal joint details, showing tendon and rubber band for flexion/extension of the finger joint. The geometrical hardstop to prevent the joint from overextending.

are discussed in Section V, followed by a conclusion in Section VI.

II. The *Dorsal Grasper*

The *Dorsal Grasper* is capable of grasping objects of various shapes and sizes through supernumerary grasping with the back of the hand by taking advantage of the user's active wrist extension; while complete SCI at C5 prevents wrist extension, people with SCI at C6 or C7 can extend their wrists up to 1.92 ± 0.82 Nm at 29.4° ± 11.5° [22]. The device is comprised of a 3D printed plastic (PLA) base situated on top of a soft cuff that is both lightweight and flexible, and holds the motor, electrical components, and updated finger design. The finger base and motor base are securely fastened with L-brackets to reduce the bending force applied to the cuff during grasping. Dowel pins (2mm) are used throughout the design for cable routing to reduce friction and wear. The weight of the device is 290 g without the wrist brace and 370 g with the brace.

A. Tendon-Driven Supernumerary Finger

We revised the fingers themselves in the current *Dorsal Grasper* version. The tendon-driven fingers are 156 mm in length and 12 mm in width, arranged in a parallel configuration with a 40 mm distance between the finger centers. Each finger consists of a proximal, middle, and distal phalanx, with lengths of 64, 50, and 42 mm, respectively (Fig. 2). These dimensions were chosen following pilot testing to ensure that fingers can effectively grasp objects ranging in diameter from 4 to 10 cm.

The fingers are driven by tendons and are positioned upright, perpendicular to the forearm for grasping. A 0.4-mm-diameter rope (PE Braided line) on a 12 mm diameter winch with a DC motor (12V with a 391:1 metal gearbox) drives finger flexion. Cast silicone rubber (Dragon Skin 10) finger pads are integrated onto the surface of each phalanx to increase the frictional coefficient and compliance between an object and the finger. The thickness of each phalange is 13 mm including the finger pad.

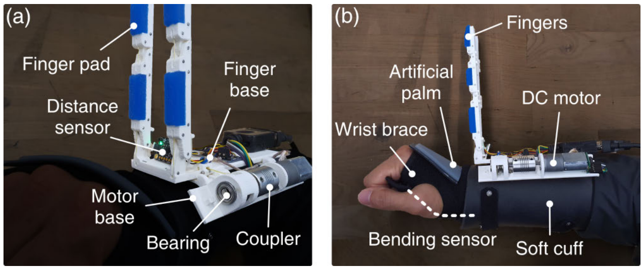

Fig. 3. The image of the *Dorsal Grasper* while wearing the device. (a) The front side of the fingers, brace, and drive-train. (b) The right side of the device, showing the bending sensor is located on the palm side of the wrist (white dotted line) embeded within the brace.

The *Dorsal Grasper* utilizes a hinge mechanism for its joints, with two phalanges being connected by a dowel pin. Unlike the preliminary version [42], the new hinge design ensures the fingers are more rigid laterally and will not deflect when lifting heavier objects. Rubber bands (Sonic Dental Supply, Bradenton, FL, USA) are preloaded across each joint to keep the fingers passively open. The shape of the fingers have been designed to prevent overextending,[1] and the rubber band preloads are selected to generate a slight base-to-tip, proximal to distal curling order.

B. Attachment to the Body

The attachment of the device to the forearm must be secure and comfortable to ensure effective grasping. To achieve this, as described in our previous study [42], a thermoplastic (Worbla sheet, TAP Plastics) forearm cuff is used with soft foam padding to protect the skin and distribute contact pressure. The cuff is secured onto the wearer's forearm using Velcro loops for a tight fit. The two bones (radius and ulna) in the forearm provide the capability to resist torsional rotation, thereby enhancing stability and support. The device should remain stationary on the skin, resisting the forces associated with grasping and lifting, though some slight motion may still occur due to the soft nature of the underlying tissue of the forearm and the torsional motion during supination or pronation.

Our device utilizes a commercially available wrist brace (HiRui, Xiamen, China) to integrate both an artificial palm and 1-axis flexible bending sensor (Nitto Bend Technologies, Inc., Farmington, UT, USA). The artificial palm features Velcro hooks that attach to the surface of the wrist brace (Fig. 3), and protects the opisthenar while increasing grasp friction. The bending sensor is embedded inside a small pocket on the palm of the wrist brace and measures the angle of wrist extension for both data acquisition and device control (Fig. 4). In order to compensate for individual hand shape and size variability, we calibrate the bending sensor at 0° and 45° for each participant.

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[1] This iteration of the *Dorsal Grasper* is designed for laboratory test conditions. The 'stow-ablity' function in [42] weakened the grasp, so it has been removed from the current version of the *Dorsal Grasper*.

TABLE I
DEMOGRAPHIC DATA OF THE PARTICIPANTS WITH SCI

Participant	Age	Sex	Neurologic Level of Injury	AIS Score	Year since Injury	Wrist Extension Angle	Arm Length
S1	64	Female	C5/C6	A	50+	57°	52.0 cm
S2	35	Male	C5/C6	A	16	57°	54.5 cm
S3	62	Female	C5/C6	A	45+	50°	54.0 cm
S4	42	Female	C5/C6	A	18	50°	51.5 cm

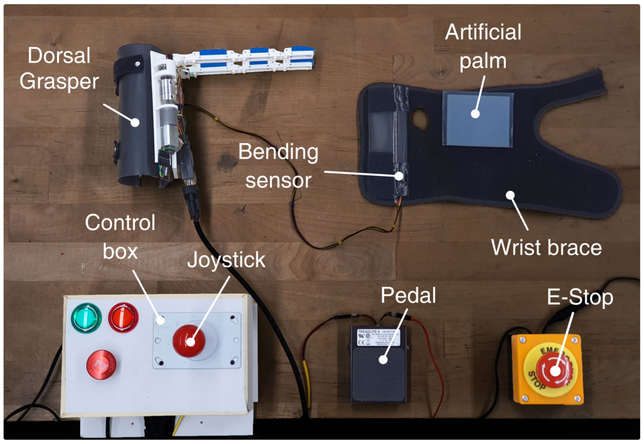

Fig. 4. The image of the *Dorsal Grasper* system, showing the device and wrist brace with the artificial palm and bending sensor. The test bed includes the control box, synchronizing pedal, and E-Stop button.

C. Control Interface and Data Acquisition

The *Dorsal Grasper* uses a control box to collect data and control the device. This box includes a large arcade joystick, an emergency stop button, two LED indicators, and an ESP32 microcontroller (Adafruit, New York, NY, USA). A DB9 serial connector enables two-way communication between a PC, the device, and the control box.

The *Dorsal Grasper* provides two control methods – joystick control and wrist angle control – manually selected by the researcher during the experiment. In the joystick control mode, the wearer inputs the grasping commands using an arcade joystick (Adafruit, New York, NY, USA) on the control box attached to the test-bench. The joystick can be toggled left and right to initiate finger flexion (grasping) and finger extension (opening), respectively, to move at a predefined speed.

In the wrist angle control mode, the device is equipped with various sensors that serve as inputs. First, the bending sensor in the palm is used to detect wrist angle. The fingers begin to close at a predefined speed when the user extends their wrist past the close-threshold angle (20°). In addition, a VL53L0X distance sensor (Adafruit, New York, NY, USA), placed at the base between the two supernumerary fingers, is used to prevent unexpected finger motion by determining when an object is within 60 mm of the gripper that the user may be attempting to grasp (Fig. 3a). To avoid detecting the back of the user's hand as an object, the sensor is angled away by 15°. Finally, the motor's magnetic encoder (part #3499, Pololu, Las Vegas, NV, USA) is used to measure motor speed and stall. At stall, grasping is complete, thus the motor stops to maintain the grasp with a non-backdrivable transmission. To clarify, once the wrist extends beyond the 20° threshold, the supernumerary fingers begin to close at a steady speed irrespective of the actual wrist angle until a reduced motor speed indicates that a grasp has been achieved. When the user relaxes their wrist extension below the open-threshold angle (10°), the supernumerary fingers move toward their original open position.

III. EXPERIMENTAL METHODS

To assess the effect of the *Dorsal Grasper*, we compared its performance to conventional unassisted tenodesis (unimanual) and bimanual grasping. We administered two experiments involving normative subjects (control group) and subjects with SCI. First, we measured their graspable workspace. Then, we asked subjects to perform a series of grasp and release tasks aimed at emulating real-world conditions. We evaluated the performance of each grasping strategy with and without the device in terms of success rate, task completion time, and wrist travel distance. As the use of the device could affect body kinematics, we also measured three distinct torso rotations: Flexion/Extension in the sagittal plane, transverse rotation in the transverse plane, and lateral bending in the coronal plane. It took participants approximately 2 hours to complete the study over a single session.

A. Population

Four participants with SCI were recruited in the experiment group; all four with SCI between C5-C6 level (Table I). They were initially screened to have active wrist extension capability and use of tenodesis grasping. In addition, six right-handed normative participants (5 males), aged 22-30, with unimpaired hand function were recruited for comparison. All experiments with human subjects were conducted under the IRB-approved protocol #2019-07-12348 (approved 10/04/2019, amended 07/05/2022) from the University of California at Berkeley. Informed consent was received from all human subjects before experimentation.

B. Motion Capture System and Markers

Three-dimensional kinematic data of the upper-limb and body movement was collected using the Impulse X2 motion capture system (PhaseSpace Inc., San Leandro, CA, USA), sampled at 60 Hz. Five motion cameras around the experimental area captured the body and test object's motion by tracking the position of light-emitting diodes (LEDs). LED markers were placed on the following locations (Fig. 5): a body harness, a strap around the upper-arm, on the *Dorsal Grasper* around the forearm, the experiment table, and the experimental objects. One LED marker on the table was electrically connected to the synchronizing pedal to sync the

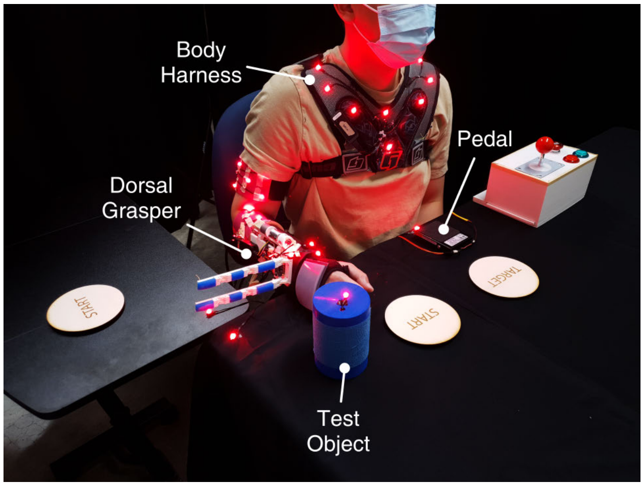

Fig. 5. The table setup and LED markers for the experiment. LEDs are attached to the body and the table.

motion capture system to the *Dorsal Grasper* data. Redundant markers were included to reconstruct occluded markers.

For accurate capture of markers during the experiment, motion capture recordings were reviewed using Recap2 post-processing software (PhaseSpace Inc., San Leandro, CA, USA). The body's neutral posture was determined by calculating averages from a calibration trial.

C. Graspable Workspace

The graspable workspace is the distance from the origin on the table in which the person can grasp and lift an object (Fig. 6a); the user's sitting position was fixed. We used a cylindrical object with 15 cm height, 5 cm diameter, and 80 g in weight; its edges are additionally tapered to make the object easier to slide into the hand. This object's bottle-like geometry was specifically chosen because a power grasp could be reliably employed with the tested unimanual grasp mode, allowing for an assessment across different grasping methods. We put the object in a specific direction and distance from the reference origin point on the table and asked participants to grasp and lift the object. If the participant successfully performed the task, we increased the object's distance until they could no longer grasp and lift it, thus defining the graspable workspace in 2-dimensional space. Workspace measurements were performed in six directions within the extended first quadrant.

D. Functional Workspace and Body Compensation Test

We designed a Functional Workspace and Body Compensation Test (FWBCT) to quantitatively evaluate the *Dorsal Grasper*'s grasping success rate and how the device influenced users' motion at two different points of the workspace (Fig. 6b). Participants were asked to grasp, lift, transfer, and release the experimental object from one of the two start areas to the target area. When the subjects were asked to grasp the object from start area 1 and release it on the target area, we call this task *Anterior*. When an object was grasped from the start area 2 to the target area, we call that task *Lateral*.

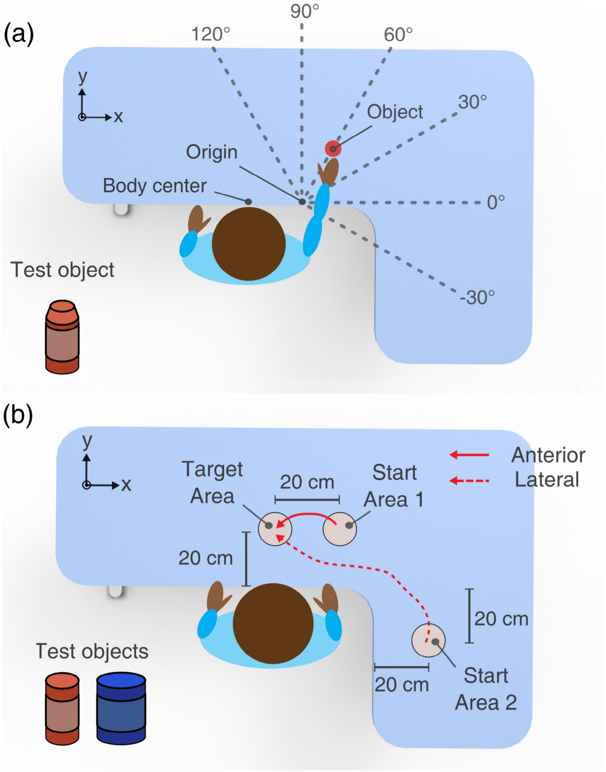

Fig. 6. Diagram of experiments. (a) Graspable workspace measurement, showing six different directions from the origin. (b) The experimental setup for the modified Grasp and Release Test, showing two different tasks: *Anterior* and *Lateral*.

This later setup specifically placed the objects on the right side of the body to emulate the scenario where the wheelchair cannot access the table from the front. We asked subjects to place the objects in an upright orientation on the target area and to push the synchronizing pedal before and after performing each task. The task was considered successful if completed within 30 seconds, otherwise it was considered a failure; failed tasks were not repeated. We used two 3D-printed cylindrical objects for the FWBCT. The small object was 15 cm in height, 5 cm in diameter, and 150 g in weight; the large object is 15 cm in height, 8 cm in diameter, and 500 g in weight. While the large object wass only suitable for bimanual grasping with SCI, the small object could be grasped unimanually (using tenodesis grasp) by some; both objects could be unimanully grasped by the normative participants. Both objects included self-adhesive bandages wrapped around the middle to increase friction between the plastic material and the hand. All tasks were repeated three times, self-paced, and performed after a 10-minute pre-training prior to trial recordings. None of the participants elected to use the full 10 minutes of pre-training, expressing comfort and readiness with the device.

E. Experimental Condition

For both evaluations, we prepared a height-adjustable L-shaped desk so that participants' upper limbs were at a comfortable elevation from the table. They were asked to fix their wheelchair position during the experiment after adjusting

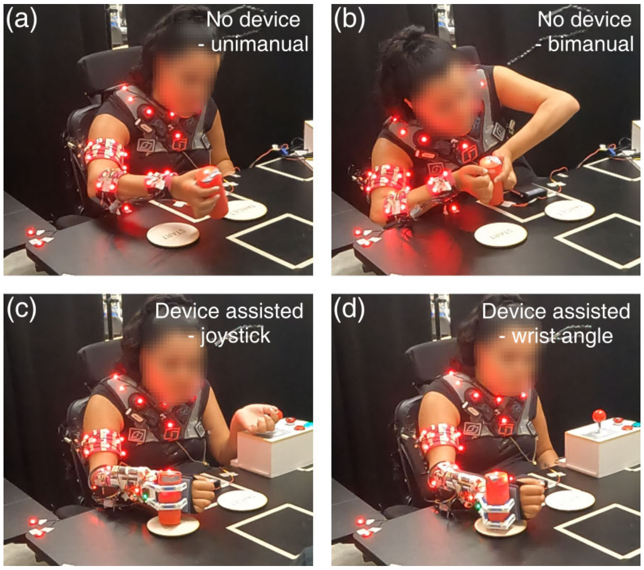

Fig. 7. Four different grasping methods performed by the subject with SCI. (a) Unimanual (one hand) and (b) bimanual (two hands) grasping without the device. (c) joystick and (d) wrist angle control mode with the device.

their body position. However, they were allowed to rotate and lean their body in their chair. In both workspace and FWBCT experiments, we asked participants to perform the tasks with four different grasping methods (Fig. 7): *unimanual* (one hand) and *bimanual* (two hands) grasping without the device; *joystick* and *wrist angle* control mode with the device. Note, bimanual manipulation was performed with the inside of the participants' wrists, whether or not they were wearing the device akin to how they perform it in their daily lives. After completing the tasks using the device, participants were then asked to repeat unimanual and bimanual FWBCT while wearing the device – but not using it – to evaluate how the device's weight and presence influence a non-device functional outcome in terms of success rate. Normative participants were not asked to perform bimanual grasping in the workspace experiment, while they were asked to do so in the FWBCT experiment to allow us to compare body kinematics between the two populations.

F. Interview Analysis

Following the completion of all constructed tasks, we asked them to perform grasp and manipulation tasks with seven common objects: a soccer ball, baseball, football, deodorant, soda can, tupperware, and fork (see the supplementary video). After all of prepared tasks, we conducted semi-structured interviews with each participant with SCI. The interview guide covered a range of topics, including the participants' perceptions of and experiences with the *Dorsal Grasper*, their preferences regarding control modes, the comfort and usability of the device, as well as its potential for commercialization and adaptability. For the comfort, we asked the subjects to rate the overall comfortability of the device on a scale of 0 to 5, with 0 being uncomfortable, and 5 being very comfortable.

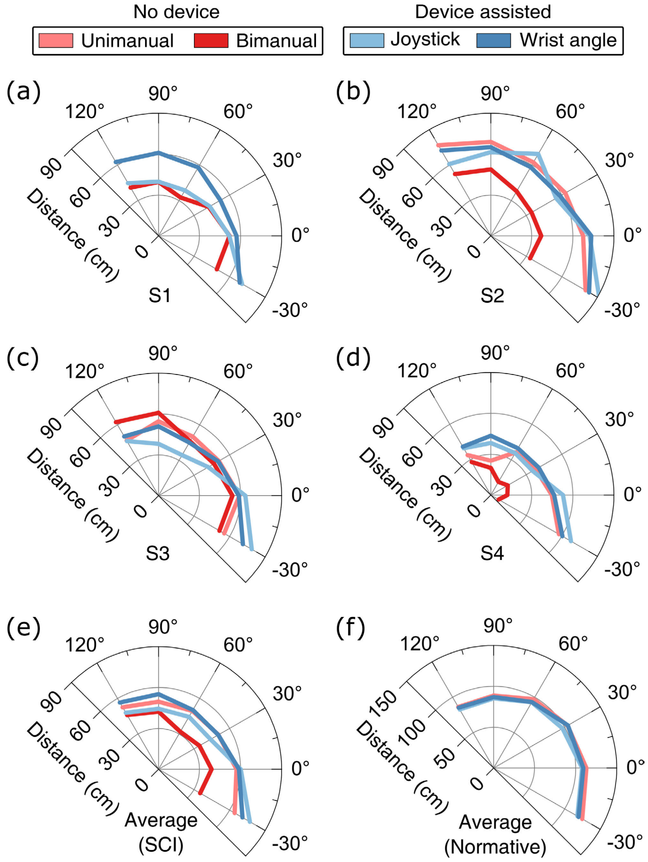

Fig. 8. Results of graspable workspace. (a-d) Workspace results from individuals with SCI S1-S4, respectively. Average graspable workspace area from subjects with SCI (e) and normative subjects (f).

IV. RESULTS

A. Graspable Workspace

The graspable workspace measurements are shown in Fig. 8. The participants with SCI exhibited diverse tendencies across individuals and grasp methods, while normative participants showed more consistent workspaces across methods, whether with or without the device. Participant S1, whose fingers were substantially flexed, displayed no graspable workspace data for unimanual grasping, they could not grip even the 50 mm object. Notably, this subject utilized the left hand (device not worn) on the table for body balance, resulting in a larger workspace for the wrist angle control mode compared to the joystick control mode, which necessitates using the left hand to operate the device.

Participant S2 exhibited the largest graspable workspace among participants with SCI in both unimanual and device-assisted grasping. For the S3 subject, the results indicate that unassisted grasping yielded a larger workspace in certain directions compared to device-assisted grasping. Interestingly, subject S3 exhibited the largest workspace in bimanual grasping when reaching in front (120° and 90°). This participant leaned forward substantially and used their elbows to support their body, allowing them to reach and grasp objects over 60 cm from the origin. However, other participants with SCI achieved bimanual grasping generally with the smallest workspace among all the grasping methods tested. Subject S4

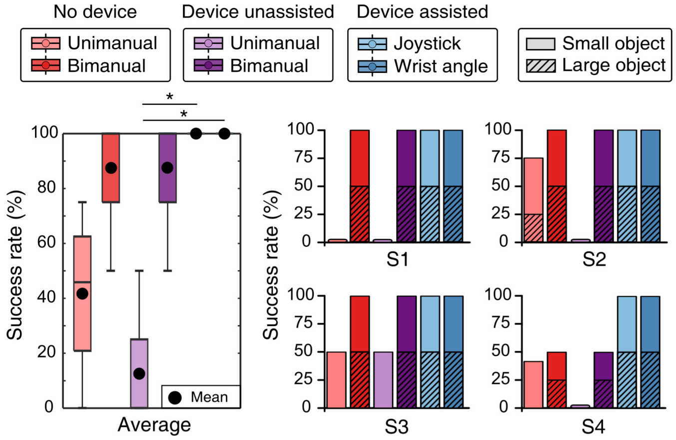

Fig. 9. Success rate of the grasp and release test from SCI population. Unassisted grasping includes both unimanual and bimanual grasping without assistance from the worn device. Asterisks denote statistical significance after paired t-tests with Bonferroni correction for multiple comparisons (*$p < 0.05$).

exhibited the smallest workspace among all participants with SCI across all grasping methods measured.

On average (Fig. 8e), individuals with SCI demonstrated similar results between unimanual grasping and device-assisted grasping, while bimanual grasping yielded the smallest workspace. In general, graspable workspaces with one hand grasping (unimanual grasping, joystick, and wrist angle control mode) tended to increase as the reaching angle decreased, which is expected considering that a lower reaching angle corresponds to reaching to the side of the body. This trend was also observed in the normative subjects' results (Fig. 8f). In contrast, bimanual grasping showed a tendency to decrease the workspace with lower reaching angle. Thus, the difference between bimanual grasping and the other methods increased as the angle decreased.

B. Functional Workspace and Body Compensation Test

1) Success Rate: Fig. 9 presents the success rates of the FWBCT for subjects with SCI; normative participants achieved success in every task and are thus omitted. The average success rate for conditions without the device, representing grasping with the participants' own hand(s), was 64.7 ± 17.3%. Most notably, upon wearing the device, no failures occured in performing the FWBCT using the 'Device assisted' modes. However, in 'Device unassisted', unimanual grasping success rate dropped significantly from 41.7 ± 31.2% to 12.5 ± 25.0% while bimanual grasping success rate remained the same. We attribute this difference to subjects S2 (87.5% dropping to 50%) and S4 (45.8% dropping to 25%); the participants failed to grasp the large object in all tasks when wearing the device but using their own hand, despite successfully performing the *Anterior* task with the large object using unimanual grasping in the 'No device' condition. Subjects S1 and S3 success rates for both 'No device' and 'Device unassisted' remained the same at 50% and 75%, respectively. Thus, for some subjects and objects, the device (possibly the wrist brace) may impede the tenodesis grasp.

2) Completion Time and Travel Distance: The results for the completion time and wrist trajectory of the FWBCT, along with the mean difference between the two populations, are presented in Fig. 10. The normative population demonstrated more consistent completion times and travel distances across the different grasping methods than subjects with SCI – mean standard deviations of 0.84 compared to 3.30 s for completion times and 81.1 compared to 294.7 mm for travel distances, respectively. Unimanual and bimanual grasping methods exhibited shorter completion times compared to the joystick and wrist angle control modes in normative subjects; this may be attributed to the fact that using the device requires additional time to operate the fingers with fixed speed, whereas bare hands can accomplish a grasp more quickly. In normative participants, unimanual grasping without a device exhibited the shortest wrist travel distance, while bimanual grasping displayed the largest, despite similar completion times. From observation, participants maintained an unusually rigid posture during bimanual grasping; their elbows were largely extended and they rotated the whole torso rather than just their arms as in unimanual grasping, leading to the observed longer distances.

The results obtained from subjects with SCI exhibited greater variability across participants and grasping methods. Specifically, when attempting to grasp the large object using unimanual grasping (i.e. without the device), only one SCI subject successfully, though slowly, performed the *Anterior*, while none of the participants could perform the unassisted unimanual *Lateral*. On the other hand, the utilization of the *Dorsal Grasper* resulted in successful grasps across all participants during the 'large object Lateral FWBCT' task, indicating a performance improvement and normalization across subjects. This suggests that the device is beneficial even for individuals with severe and varied hand dysfunction due to SCI impairment. However, device-assisted grasping did not consistently lead to reduced completion times. In addition to needing to first orient the gripper around the object and then operate the fingers, SCI participants in particular also faced mobility challenges that required them to spend more time rotating their bodies towards the object. Conversely, device-assisted grasping did result in the shortest travel distances. Although time was not significantly affected, the device enabled a more efficient grasping action for the SCI participants.

To compare the two subject groups, we calculated the mean differences between them (Fig. 10, bottom row), where positive values mean subjects with SCI took more time or their hand travelled further to complete tasks. Notably, the differences in completion times and wrist travel distance exhibited a decreasing trend across the grasping methods, with unimanual, bimanual grasping, and device-assisted modes, in that order. While participants with SCI displayed substantial variability across grasping methods, the mean difference results, for both travel distance and completion time, suggest that performance in FWBCT using the device approaches that of normative participants. However, the observed diminishing differences were also in part due to a worsening grasp performance with the device in the normative population.

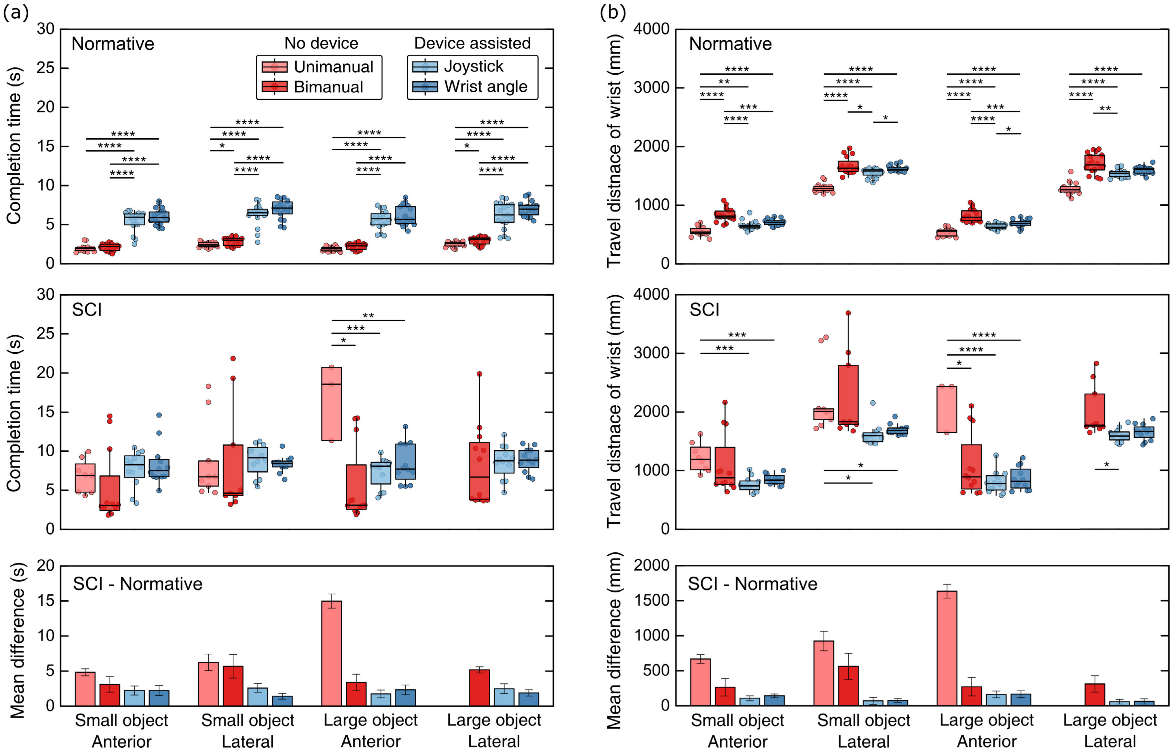

Fig. 10. Results of the (a) completion time and (b) wrist travel distance of the FWBCT. The results include data from the normative population, subjects with SCI, and the mean differences between the two populations, shown from top to bottom, respectively. The mean differences are presented as the mean difference ± standard error of the mean. Asterisks denote statistical significance after two-sampled t-tests with Bonferroni correction for multiple comparisons (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, ****$p < 0.0001$).

3) Torso Rotation: The results of torso rotations during the FWBCT are presented in Fig. 11. We defined the range of motion as the angular difference between the maximum and minimum angles during each FWBCT task. Due to kinematic constraints, during *Lateral* with bimanual grasping, both subject populations exhibited notably larger ranges of motion compared to *Anterior*. Among normative subjects, unimanual grasping consistently exhibited the least body rotation across all task configurations, even when comparing *Lateral* tasks to *Anterior*. In contrast, among SCI subjects, device-assisted modes often resulted in significantly lower torso rotation compared to modes without the device. Therefore, the device assisted modes consistently provided significant reductions in transverse and lateral compared with bimanual grasping, and sometimes unimanual grasping as well. While normative subjects tended to show larger ranges of motion with bimanual grasping than with unimanual grasping, SCI subjects during the ‘large object Anterior FWBCT’ task exhibited median values for unimanual grasping larger than those for bimanual grasping. For both populations, differences between the joystick and wrist angle control modes were not substantial, except for the ‘large object Lateral FWBCT’ task in flexion/extension from the SCI subjects.

The mean difference in the range of motions between SCI and normative subjects is shown at the bottom of Fig. 11c-e, where positive values mean subjects with SCI rotated over a larger range than normative subjects about a rotation axis. In unimanual grasping, SCI subjects exhibited a larger range of motion across all torso rotations. Due to weaker arm and hand strength, SCI subjects may require further body adjustments to successfully perform the tasks. During bimanual grasping for *Lateral*, both subject groups rotated their torsos to face the start area but, likely owing to greater body mobility, normative subjects had greater flexion/extension and transverse rotations than that of SCI subjects. On the other hand, subjects with SCI had to leverage more lateral bending for these tasks. However, with device-assisted modes, subjects with SCI were able to reach objects without large lateral bending resulting in smaller differences (<5°) between the two populations.

C. Common Interview Theme From Subjects With SCI

When asked about the FWBCT tasks, all subjects with SCI expressed a preference for using the device over their own hand(s). Subject S3 specifically noted, “This [the device] is definitely better for things that are super heavy.” Also, subject S4 commented, “I felt like I didn’t have to extend my body as much and I didn’t have to use as many muscles with the device. So that’s the benefit.”

Regarding comfort, results were more varied. While subjects S1, S2, and S4 rated the device a 4 out of 5, subject S3 rated it 2.5 out of 5. Subject S4 mentioned that the weight of the device was the only complaint: “ It was just a little heavy.” Subject S3 remarked, “It’s not the most comfortable thing, but now I don’t know if it was the device or the sensors and the vest [body harness].” Subjects S1 and S3 disliked the relatively long length of the fingers remarking they might be cumbersome. Subject S2 said, “It feels like it [the device]…restrict my wrist a little.”

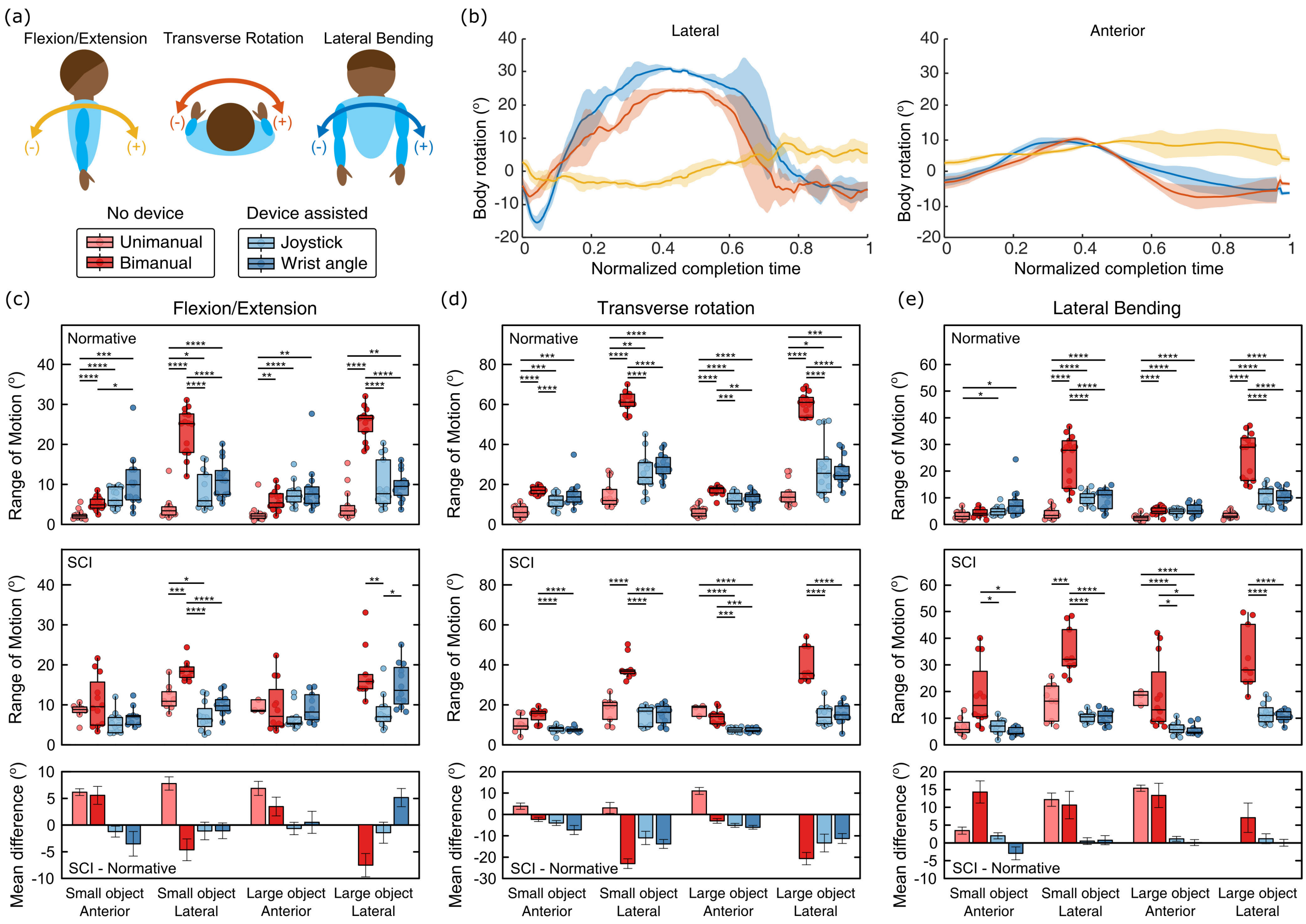

Fig. 11. Torso rotation results during the FWBCT. (a) Three torso rotations and their sign convention. (b-c) Representative torso rotation during the FWBCT with the large object using bimanual grasping, with solid colored lines indicating the average and colored areas representing the standard deviation. Data represented here are from all three trial repetitions from one subject with SCI. (d-f) The average range of torso rotations during the FWBCT. Asterisks denote statistical significance after two-sampled t-tests with Bonferroni correction for multiple comparisons (*p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.0001).

Generally, subjects preferred using the joystick control mode for the heavier object, stating that it felt less dependent on their wrist and stronger, as they could apply grasp force from the device toward the object and back of the hand. For example, subject S1 mentioned, “It seemed like I had a firmer grip on the heavier stuff with the joystick.” While Subject S3 also commented about similar advantages of the joystick control, they also mentioned advantages of the wrist control by adding, “I think having to keep the wrist extended makes it feel more like it’s following your movement, so it feels more integrated.” Subject S1 also found that “the wrist angle was more intuitive than the joystick.”

When asked about usability and use cases, perspectives on potential translational applications varied. Across the subjects, they proposed using the device for “getting hot stuff out of the oven,” “grabbing things off the [grocery store] shelf,” “doing kitchen stuff,” and “open[ing] the drawer.” These tasks are aligned with the ability of the device to apply large grip forces with a single arm *lateral* to the body. Regardless, subjects S1 and S2 expressed skepticism about real-world adoption. For example, subject S1 commented, “Personally, I don’t know that it would greatly enhance what I can already do.” Subject S4 however emphasized the benefit that comes with performing grasping tasks independently: “It eliminates an entire conversation that I have to have the first thing in the morning…with a caregiver.” If the *Dorsal Grasper* can translate to the home, it would provide this benefit.

D. Observations of Onboard Device Sensor Data

Throughout the study, we observed variations in the grasping phase between the test objects in the wrist angle control mode. To further investigate, we segmented the FWBCT data into five distinct phases: approach, grasp, transport, release, and return. We illustrate one subject performing the *Anterior* in Fig. 12). Following the hand’s approach to the start area, the subject extended the wrist to close the supernumerary fingers around the object, then transported it to the target area, released the object, and finally returned to the origin. In the case of the smaller object, the subject completed the grasping phase when the motor stopped and moved the object to the target area. However, for the larger object, the subject attempted further wrist extension (indicated by the red

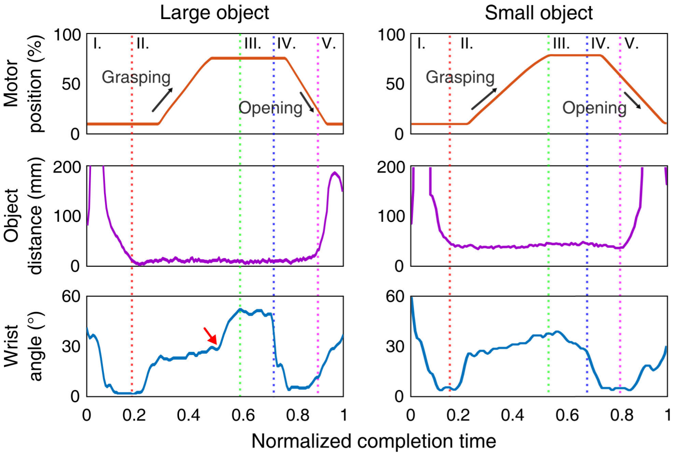

Fig. 12. Representative sensor readings from *Anterior*. Dotted lines show transitions between grasping phases: I. approach, II. grasp, III. transport, IV. release, and V. return. Object distance from the sensor measurement, with a range up to 1000 mm, displayed from 0 to 200 mm. The selected range highlights the most critical interactions for the study. Initial and final wrist angle was not controlled for and was a function of how the user decided to press the synchronizing pedal.

arrow) after the motor stopped, before starting the transport phase. This second wrist extension effort was observed in two subjects with SCI in the FWBCT with the larger object. From this observation, we hypothesize that some subjects could perceive and intuitively increase grasp security as needed while using the device.

V. DISCUSSION

For individuals with SCI, unimanual and bimanual grasping demonstrated complementary strengths and weaknesses. We first confirmed that unimanual grasping provided a larger graspable workspace (Fig. 8e) but was largely limited to small and light objects (Fig. 9). In contrast, bimanual grasping could handle larger and heavier objects but with a smaller workspace. The *Dorsal Grasper* combined the strengths of both approaches, offering a large graspable workspace and the capability to grasp large and heavy objects, making it a versatile option for a wide range of tasks. In this work, we also quantified the efficiency of the movement by tracking completion times and wrist travel distances (Fig. 10) and trunk movements (Fig. 11) and compared 'no device' to 'device assisted' test conditions. All three measures confirmed that the *Dorsal Grasper* provided either neutral outcomes – unchanged completion times – or benefits – reduced wrist travel distances and trunk motions – for subjects with SCI. In comparing these measures from subjects with SCI to subjects with normative hand and arm function, we found that these groups performed more similarly when using the device; while this is associated with improved performance in subjects with SCI, it is also amplified by a reduction in performance by normative subjects.

A. Differences Between Subjects With SCI

While all subjects with SCI were classified with AIS grade A, variations in other factors such as age, sex, years post-injury, maximum wrist extension angle, and arm length (Table I) likely contributed to observed differences between individuals. Individuals could also differ in the amounts of rehabilitation received, remaining muscle strength, and range of motion in affected body parts, resulting in different outcomes across subjects. Specifically, subject S2 had the longest arm length which naturally extended their reach (Fig. 8b), showing the largest workspace with one-handed grasping methods (unimanual and device assisted grasping). On the other hand, subject S3, who utilized substantial torso flexion towards the table, showed the largest bimanual graspable workspace by compensating for reach limitations – even larger than that of subject S2, who had the longest arm length, shortest years post-injury, youngest age, and a different sex (Fig. 8c). By expanding the number of subjects, future work could further investigate these confounding factors.

One of the goals of supernumerary dorsal fingers is to enable grasping of heavier and larger objects without limiting people from using tenodesis grasping for small, light objects. However, according to the results of the FWBCT, using tenodesis grasping under 'Device unassisted' showed decreased success rate compared to 'No device' (Fig. 9), specifically for S2 and S4. The added weight of the device required more effort for individuals with reduced arm strength. The material around the wrist may also impede wrist extension motion, and the resulting grasp aperture control. Regardless, we note that device presence had no measured negative effect on S1 and S3, and even S3 reported that the use of the wrist brace increased security and enhanced grasping ability, thus some individuals can still perform typical or even enhanced unimanual tenodesis grasping with the current version of the device on. Future work will explore device customization to reduce weight and minimize interference with tenodesis grasping across individual variability. For example, a redesign could locate the motor farther away from the hand to reduce weight and even place it on the wheelchair with additional mechanical transmission. However, some individuals may prefer a more compact, standalone device to ease donnability despite the increased weight.

B. Observations of User Control

Both the joystick and wrist angle control modes of the device yielded similar results in terms of workspace and FWBCT performance. Despite this similarity, these control modes offered distinct functionalities tailored to different user requirements, with each appealing to SCI subjects for different applications. The joystick control mode allowed for precise manual control over the device, enabling users to adjust their grasp according to the object's shape and size. The wrist angle control mode offered an intuitive approach, using wrist extension similar to tenodesis grasp. One of the advantages of wrist angle mode over joystick mode was the liberation of the opposite hand; the left hand could brace the body during reaching tasks, for example. In some cases, the joystick mode exhibited a larger workspace than the wrist control mode, which motivates future work generating adaptable user inputs.

The supernumerary fingers squeeze an object against the back of the hand, thus, both the user and device simultaneously act on the object with opposing grasp forces. As a result, we observed that people with SCI can perceive and respond to changes in object mass to improve grasp security with additional wrist extension (Fig. 12). As opposed to devices that constrain the fingers, people now compensate for grasp state with body-power without latency or physical resistance. These advantages may assist in grasping objects with various properties, such as soft or brittle items. For example, grasping a brittle object requires delicate control of the grasping force, which can be achieved with user participation during the grasping phase. To enhance our understanding of how users modify their wrist angle in response to objects' properties, monitoring muscle activities and grasping forces applied by the robotic fingers would be insightful to explore in the future. More sophisticated motor control methods could also be explored beyond mere wrist angle control that involves on/off closing and opening of fingers based on motor encoder data, and additional haptic feedback from the supernumerary robotic fingers may provide useful information to grasp and manipulate delicate objects. Further study of user participation in such collaborative grasping for human-robot systems is left to future work.

C. Study Limitations

In this study, we define the graspable workspace and functional workspace using a specific cylindrical object. Workspace dimensions may vary substantially due to changes in an object's properties such as weight, dimensions, surface roughness, and weight distribution, as well as the three-dimensional location of the object and its shape. These variations could potentially affect the performance of different grasping methods. For example, if the object were located in a higher position, e.g., at eye level, bimanual grasping might exacerbate physical constraint of our body moreso than seen in the present work.

This study focused on the kinematic changes observed with the introduction of the *Dorsal Grasper* in a structured laboratory setup. Future work needs to include manipulation tasks in daily living with the device outside the lab. While the subjects with SCI conducted semi-unstructured object manipulation tasks before the interview to elicit various responses, these results cannot replace in-home translational studies. Future studies could also measure how the device varies and replaces existing grasp strategies in real-world tasks, as discussed in this grasp taxonomy [44].

Senses of embodiment such as ownership, agency, and self-location [45] influence adoption of wearable robotic systems; these attributes are significant in supernumerary robotic fingers or limbs systems, which have not yet been extensively studied [46]. While we did not directly ask subjects about their senses of embodiment of the device, some participants expressed these feelings through comments such as "feels more integrated" and "feels like a part of my arm." Future work will include quantitative analysis of embodiment and ownership of the device by users [47], as well as usability assessments [48], [49]. Additionally, a subject reported not feeling the need to "use as many muscles with the device." Quantifying muscle usage in future work could allow researchers to objectively monitor how the device influences users' activation patterns during tasks, and provide valuable understanding beyond kinematic changes.

VI. CONCLUSION

Supernumerary grasping with the back of the hand enables people – with varied hand muscle stiffness or contracture in the fingers resulting from SCI – to grasp more objects across a larger workspace. It is not uncommon for wheelchair users to need to retrieve items from inaccessible spaces such as the refrigerator, kitchen counter or inaccessible table with no leg/foot clearance to approach head-on. This highlights the *Dorsal Grasper*'s important capability to expand the reachable workspace of users while avoiding the need to perform large torso movements. The laboratory study motivates future device development for translation and testing of utility in the home. This will provide valuable insights into the device's performance and usability in real-world settings, potentially uncovering new challenges and opportunities for improvement.

REFERENCES

[1] A. Krassioukov, "Autonomic function following cervical spinal cord injury," *Respiratory Physiol. Neurobiol.*, vol. 169, no. 2, pp. 157–164, Nov. 2009.

[2] Y. Kang et al., "Epidemiology of worldwide spinal cord injury: A literature review," *J. Neurorestoratol.*, vol. 6, pp. 1–9, Dec. 2017.

[3] J. R. Tomasone, N. N. Wesch, K. A. M. Ginis, and L. Noreau, "Spinal cord injury, physical activity, and quality of life: A systematic review," *Kinesiol. Rev.*, vol. 2, no. 2, pp. 113–129, May 2013.

[4] M. Wyndaele and J.-J. Wyndaele, "Incidence, prevalence and epidemiology of spinal cord injury: What learns a worldwide literature survey?" *Spinal Cord*, vol. 44, no. 9, pp. 523–529, Sep. 2006.

[5] *Traumatic Spinal Cord Injury Facts and Figures at a Glance*, National Spinal Cord Injury Statistical Center, Birmingham, U.K., 2022.

[6] S. Mateo, A. Roby-Brami, K. T. Reilly, Y. Rossetti, C. Collet, and G. Rode, "Upper limb kinematics after cervical spinal cord injury: A review," *J. Neuroeng. Rehabil.*, vol. 12, no. 1, pp. 1–12, 2015.

[7] K. D. Anderson, "Targeting recovery: Priorities of the spinal cord-injured population," *J Neurotrauma*, vol. 21, no. 10, pp. 1371–1383, Oct. 2004.

[8] A. Bryden, A. Peljovich, H. Hoyen, G. Nemunaitis, K. Kilgore, and M. Keith, "Surgical restoration of arm and hand function in people with tetraplegia," *Topics Spinal Cord Injury Rehabil.*, vol. 18, no. 1, pp. 43–49, Jan. 2012.

[9] B. T. Smith, M. J. Mulcahey, and R. R. Betz, "Quantitative comparison of grasp and release abilities with and without functional neuromuscular stimulation in adolescents with tetraplegia," *Spinal Cord*, vol. 34, no. 1, pp. 16–23, Jan. 1996.

[10] D. Apple, R. Cody, and A. Allen, "Overuse syndrome of the upper limb in people with spinal cord injury. Physical fitness: A guide for individuals with spinal cord injury," *J. Rehabil. Res. Dev.*, vol. 26, pp. 97–108, Jan. 1996.

[11] E. Y. Chang, A. I. McPherson, R. C. Adolf, Y. Gloumakov, and H. S. Stuart, "Modulating wrist-hand kinematics in motorized assisted grasping with C5-6 spinal cord injury," *IEEE Trans. Med. Robot. Bionics*, vol. 6, no. 1, pp. 189–201, Feb. 2024.

[12] A. I. W. McPherson, V. V. Patel, P. R. Downey, A. A. Alvi, M. E. Abbott, and H. S. Stuart, "Motor-augmented wrist-driven orthosis: Flexible grasp assistance for people with spinal cord injury," in *Proc. 42nd Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Jul. 2020, pp. 4936–4940.

[13] M. W. Keith, P. H. Peckham, G. B. Thrope, J. R. Buckett, K. C. Stroh, and V. Menger, "Functional neuromuscular stimulation neuroprostheses for the tetraplegic hand," *Clin. Orthopaedics Rel. Res.*, vol. 233, pp. 25–33, Aug. 1988.

[14] K. L. Kilgore, K. D. Anderson, and P. H. Peckham, "Neuroprosthesis for individuals with spinal cord injury," *Neurological Res.*, vol. 45, no. 10, pp. 893–905, Oct. 2023.

[15] E. D. L. D. Santos, M. C. Gelain, E. Krueger, G. N. Nogueira-Neto, and P. Nohama, "Artificial motor control for electrically stimulated upper limbs of plegic or paretic people," *Res. Biomed. Eng.*, vol. 32, no. 2, pp. 199–211, Jun. 2016.

[16] S. Micera, T. Keller, M. Lawrence, M. Morari, and D. B. Popovic, "Wearable neural prostheses," *IEEE Eng. Med. Biol. Mag.*, vol. 29, no. 3, pp. 64–69, May 2010.

[17] M. Stokes and R. Cooper, "Muscle fatigue as a limiting factor in functional electrical stimulation: A review," *Physiotherapy Pract.*, vol. 5, no. 2, pp. 83–90, Jan. 1989.

[18] J. M. Khalifeh et al., "Nerve transfers in the upper extremity following cervical spinal cord injury. Part 1: Systematic review of the literature," *J. Neurosurgery, Spine*, vol. 31, no. 5, pp. 629–640, Nov. 2019.

[19] J. A. Dunn, K. A. Sinnott, A. G. Rothwell, K. D. Mohammed, and J. W. Simcock, "Tendon transfer surgery for people with tetraplegia: An overview," *Arch. Phys. Med. Rehabil.*, vol. 97, no. 6, pp. S75–S80, Jun. 2016.

[20] J. Fridén and A. Gohritz, "Tetraplegia management update," *J. Hand Surg.*, vol. 40, no. 12, pp. 2489–2500, Dec. 2015.

[21] C. M. Curtin, D. R. Gater, and K. C. Chung, "Upper extremity reconstruction in the tetraplegic population, a national epidemiologic study," *J. Hand Surgery*, vol. 30, no. 1, pp. 94–99, Jan. 2005.

[22] Y.-S. Kang, Y.-G. Park, B.-S. Lee, and H.-S. Park, "Biomechanical evaluation of wrist-driven flexor Hinge orthosis in persons with spinal cord injury," *J. Rehabil. Res. Develop.*, vol. 50, no. 8, 2013.

[23] E. Y. Chang, R. Mardini, A. I. McPherson, Y. Gloumakov, and H. S. Stuart, "Tenodesis grasp emulator: Kinematic assessment of wrist-driven orthotic control," in *Proc. Int. Conf. Robot. Autom. (ICRA)*, May 2022, pp. 5679–5685.

[24] S. Khalid, F. Alnajjar, M. Gochoo, A. Renawi, and S. Shimoda, "Robotic assistive and rehabilitation devices leading to motor recovery in upper limb: A systematic review," *Disab. Rehabil., Assistive Technol.*, vol. 18, no. 5, pp. 658–672, Jul. 2023.

[25] R. Readioff, Z. K. Siddiqui, C. Stewart, L. Fulbrook, R. J. O'Connor, and E. K. Chadwick, "Use and evaluation of assistive technologies for upper limb function in tetraplegia," *J. Spinal Cord Med.*, vol. 45, no. 6, pp. 809–820, Nov. 2022.

[26] M. Sarac, M. Solazzi, and A. Frisoli, "Design requirements of generic hand exoskeletons and survey of hand exoskeletons for rehabilitation, assistive, or haptic use," *IEEE Trans. Haptics*, vol. 12, no. 4, pp. 400–413, Oct. 2019.

[27] A. S. Gorgey, "Robotic exoskeletons: The current pros and cons," *World J. Orthopedics*, vol. 9, no. 9, pp. 112–119, Sep. 2018.

[28] N. Jarrasse and G. Morel, "Connecting a human limb to an exoskeleton," *IEEE Trans. Robot.*, vol. 28, no. 3, pp. 697–709, Jun. 2012.

[29] C. C. Shepherd and S. H. Ruzicka, "Tenodesis brace use by persons with spinal cord injuries," *Amer. J. Occupational Therapy*, vol. 45, no. 1, pp. 81–83, Jan. 1991.

[30] L. Cappello et al., "Assisting hand function after spinal cord injury with a fabric-based soft robotic glove," *J. Neuroeng. Rehabil.*, vol. 15, no. 1, pp. 1–10, Dec. 2018.

[31] H. K. Yap et al., "A fully fabric-based bidirectional soft robotic glove for assistance and rehabilitation of hand impaired patients," *IEEE Robot. Autom. Lett.*, vol. 2, no. 3, pp. 1383–1390, Jul. 2017.

[32] P. Polygerinos et al., "Towards a soft pneumatic glove for hand rehabilitation," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Nov. 2013, pp. 1512–1517.

[33] C. Venugopal, G. Pak, S. Florea, J. Perkins, and C. Anderson, "Assistive hand device using silicone actuators," in *Proc. IEEE Ind. Electron. Appl. Conf. (IEACon)*, Nov. 2021, pp. 242–245.

[34] B. B. Kang, H. Choi, H. Lee, and K.-J. Cho, "Exo-glove poly II: A polymer-based soft wearable robot for the hand with a tendon-driven actuation system," *Soft Robot.*, vol. 6, no. 2, pp. 214–227, Apr. 2019.

[35] D. Kaneishi et al., "Design and assessment of a single-size semi-soft assistive mitten for people with cervical spinal cord injuries," in *Proc. IEEE-RAS 19th Int. Conf. Humanoid Robots (Humanoids)*, Oct. 2019, pp. 614–621.

[36] C. G. Rose and M. K. O'Malley, "Hybrid rigid-soft hand exoskeleton to assist functional dexterity," *IEEE Robot. Autom. Lett.*, vol. 4, no. 1, pp. 73–80, Jan. 2019.

[37] A. T. Asbeck, S. M. M. De Rossi, I. Galiana, Y. Ding, and C. J. Walsh, "Stronger, smarter, softer: Next-generation wearable robots," *IEEE Robot. Autom. Mag.*, vol. 21, no. 4, pp. 22–33, Dec. 2014.

[38] C. J. Walsh, "Recent results from evaluation of soft wearable robots in clinical populations," in *Proc. Int Symp. Wearable Robot.*, Oct. 2018, pp. 58–62.

[39] B. Yang, J. Huang, X. Chen, C. Xiong, and Y. Hasegawa, "Supernumerary robotic limbs: A review and future outlook," *IEEE Trans. Med. Robot. Bionics*, vol. 3, no. 3, pp. 623–639, Aug. 2021.

[40] F. Y. Wu and H. H. Asada, "'Hold-and-manipulate' with a single hand being assisted by wearable extra fingers," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2015, pp. 6205–6212.

[41] I. Hussain, G. Salvietti, G. Spagnoletti, and D. Prattichizzo, "The soft-sixthFinger: A wearable EMG controlled robotic extra-finger for grasp compensation in chronic stroke patients," *IEEE Robot. Autom. Lett.*, vol. 1, no. 2, pp. 1000–1006, Jul. 2016.

[42] J. Lee, L. Yu, L. Derbier, and H. S. Stuart, "Assistive supernumerary grasping with the back of the hand," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2021, pp. 6154–6160.

[43] G. M. Yarkony, L. M. Bass, V. Keenan, and P. R. Meyer, "Contractures complicating spinal cord injury: Incidence and comparison between spinal cord centre and general hospital acute care," *Spinal Cord*, vol. 23, no. 5, pp. 265–271, Oct. 1985.

[44] A. I. W. McPherson, K. Adachi, Y. Gloumakov, and H. Stuart, "A grasp taxonomy for people with C5-7 spinal cord injury," *TechRxiv*, May 2024, doi: 10.36227/techrxiv.171625737.74343752/v1.

[45] N. Rosa, R. C. Veltkamp, W. Hürst, T. Nijboer, C. Gilbers, and P. Werkhoven, "The supernumerary hand illusion in augmented reality," *ACM Trans. Appl. Perception*, vol. 16, no. 2, pp. 1–20, Apr. 2019.

[46] K. Umezawa, Y. Suzuki, G. Ganesh, and Y. Miyawaki, "Bodily ownership of an independent supernumerary limb: An exploratory study," *Sci. Rep.*, vol. 12, no. 1, p. 2339, Feb. 2022.

[47] P. Kieliba, D. Clode, R. O. Maimon-Mor, and T. R. Makin, "Robotic hand augmentation drives changes in neural body representation," *Sci. Robot.*, vol. 6, no. 54, May 2021, Art. no. eabd7935.

[48] J. Brooke, "SUS: A quick and dirty usability scale," in *Usability Evaluation In Industry*. New York, NY, USA: Taylor & Francis, 1996.

[49] J. Dittli et al., "Mixed methods usability evaluation of an assistive wearable robotic hand orthosis for people with spinal cord injury," *J. NeuroEngineering Rehabil.*, vol. 20, no. 1, p. 162, Dec. 2023.