The Supernumerary *Dorsal Grasper* for people with C5-C7 spinal cord injury

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Abstract

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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 lighter 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. Addressing this challenge, here we present a new version of the Dorsal Grasper, a wearable device designed for those with voluntary wrist extension, providing human-robot collaborative grasping capabilities with underactuated supernumerary fingers on the back of the hand. We show that 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 experiments with 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.

To address these challenges, we explore a potential expansion of the tenodesis grasp using a supernumerary device that expands the range of graspable objects while mitigating exertion. The device is specifically designed to complement the limitations of the tenodesis grasp by performing power grasping for heavier and larger objects, thereby reducing reliance on bimanual grasping and extending the graspable workspace. Consequently, the use of the device can reduce body compensation and enhance overall functionality in indi-
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]–[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]–[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]. We propose that supernumerary grasping with the back of the hand may be helpful for people with C5-C7 SCI who maintain voluntary wrist extension but limited or no finger function. 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], [42], 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, thereby expanding the reachable workspace. Additionally, the user can utilize residual dexterity, as this format doesn’t constrain the hand.

B. Overview

A preliminary version of the device, hereby referred to as the Dorsal Grasper, was presented in [43]. In the present work, we perform a design iteration and a comprehensive analysis of device performance. Notably, we expand on the subject population to include SCI participants, in hopes of translating the device to a more real-world setting. Analysis is expanded to include both quantitative kinematic performance across different device conditions during Grasp and Release testing, as well as post-hoc qualitative device perception that includes device usage with real-world objects.

In Section II, we present the implementation and performance characterization of the updated Dorsal Grasper (Fig. 1b). 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 are discussed in Section VI followed by a conclusion in Section VII.

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 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 brace 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.

A. Tendon-driven Supernumerary Finger

In the design of the Dorsal Grasper, one of the key components is the supernumerary fingers. These 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 during the grasping motion. In order to increase the
frictional coefficient and compliance between an object and the finger, finger pads made of silicone rubber (Dragon Skin 10) are integrated onto the surface of each phalanx through casting. The thickness of each phalange is 13 mm including the finger pad.

The Dorsal Grasper utilizes a hinge mechanism for its joints, with two phalanges being connected by a dowel pin. Unlike the preliminary version [43], 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 has 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 [43], 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.

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, during stall, to determine if grasping is complete, during which the device stops the motor to maintain the grasp with a non-backdrivable transmission. 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 compare its performance to conventional unassisted tenodesis (unimanual) and bimanual grasping. We administer two experiments involving normative subjects (control group) and subjects with SCI. First, we measure their graspable workspace. Then, we ask subjects to perform a series of grasp and release tasks aimed at emulating real-world conditions. We evaluate 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 altered grasp workspace by the device could affect body kinematics, we also measure three distinct torso rotations: Flexion/Extension in the sagittal plane, transverse rotation in the transverse plane, and lateral bending in the coronal plane. It takes participants approximately 2 hours to complete the study over a single session.

A. Population

Four participants with SCI are recruited in the experiment group; all four had SCI between C5-C6 level. Three of the four participants are female and all are right handed. The ages of the subjects are 64, 35 (male), 62, and 42, later referenced by S1-S4, respectively. They are initially screened to have active wrist extension capability and use of tenodesis grasping. Six right-handed normative participants (5 males), aged 22-30, with unimpaired hand function, are included in the control group. All experiments with human subjects were conducted under the IRB-approved protocol #2019-07-12348 (approved 10/04/2019) 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 analysis of the upper-limb and body movements are made using the Impulse X2 motion capture system (PhaseSpace Inc., San Leandro, CA, USA), sampled at 60 Hz. Five motion cameras around an experimental area capture the body’s and an object’s motion by tracking the position of light-emitting diodes (LEDs). LED markers are 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 is electrically connected to the synchronizing pedal in order to sync the motion capture system to the Dorsal Grasper.

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

C. Graspable Workspace

We define a graspable workspace as the distance from the origin on the table in which the person can grasp and lift an object (Fig. 6); the user’s sitting position is fixed. We use 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. We put the object in a specific direction and distance from the reference origin point on the table and ask participants to grasp and lift the object. If the participant successfully performs the task, we increase the object’s distance until they can no longer grasp and lift it, thus defining the graspable workspace in 2-dimensional space. Workspace measurements are performed in six directions within the extended first quadrant.

D. Modified Grasp and Release Test

We design a modified Grasp and Release Test (GRT) to quantitatively evaluate the Dorsal Grasper’s grasping success rate and how the device influences users’ motion at two different points of the workspace (Fig. 6). Participants are asked to grasp, lift, transfer, and release the experimental object from one of the two start areas to the target area. When the subjects are asked to grasp the object from start area 1 and release it on the target area, we call this task front GRT. When an object is grasped from the start area 2 to the target area, we call that task side GRT. This later setup

Fig. 5. The table setup and LED markers for the experiment. LEDs are attached to the body and the table.
specifically places the objects on the right side of the bodies to emulate the scenario where the wheelchair cannot access the table from the front. The subjects are asked to place the objects in an upright orientation on the target area. They are also asked to push the synchronizing pedal before and after performing each task. The task is considered successful if it is completed within 30 seconds, otherwise it is considered a failure; failed tasks are not repeated. We use two 3D-printed cylindrical objects for the modified GRT. The small object is 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 is only suitable for bimanual grasping, the small object can be grasped unimanually (using tenodesis grasp) by some; both objects can be unimanually grasped by the normative participants. Both objects have self-adhesive bandages wrapped around the middle to increase friction between the plastic material and the hand. All tasks are repeated three times, self-paced, and performed after pre-training prior to trial recordings.

E. Experimental Condition

For both evaluations, we prepare a height-adjustable L-shaped desk so that participants’ upper limbs are at a comfortable elevation from the table. They are asked to fix their wheelchair position during the experiment after adjusting their body position. However, they are allowed to rotate and lean their body in their chair. In both workspace and GRT experiments, participants are asked 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. After completing the tasks using the device, participants are then asked to repeat unimanual and bimanual GRT while now 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 are not asked to perform bimanual grasping in the workspace experiment, while they are asked to do so in the GRT experiment to allow us to compare body kinematics between the two populations.

F. Interview Analysis

Following the completion of all tasks, we conduct semi-structured interviews with each participant with SCI. The interview guide covers 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.
Participant S2 exhibits 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 yields a larger workspace in certain directions compared to device-assisted grasping. Interestingly, subject S3 exhibits 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 show that bimanual grasping generally has the smallest workspace among all the grasping methods tested. Subject S4 exhibits the smallest workspace among all participants with SCI across all grasping methods measured.

On average (Fig. 8f), individuals with SCI demonstrate similar results between unimanual grasping and device-assisted grasping, while bimanual grasping yields the smallest workspace. In general, graspable workspaces with one hand grasping (unimanual grasping, joystick, and wrist angle control mode) tend 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 is also observed in the normative subjects’ results (Fig. 8f). In contrast, bimanual grasping shows a tendency to decrease its workspace with lower reaching angle. Thus, the difference between bimanual grasping and the other methods increases as the angle decreases.

### B. Modified Grasp and Release Test

1) **Success rate:** Fig. 9 presents the success rates of the modified GRT 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), is 64.7 ± 17.3%. Most notably, upon wearing the device, no failures occur in performing the GRT using the ‘Device assisted’ modes. However, in ‘Device unassisted’, unimanual grasping success rate drops significantly from 41.7 ± 31.2% to 12.5 ± 25.0% while bimanual grasping success rate remains the same. This difference is attributed to subjects S2 (87.5% dropping to 50%) and S4 (45.8% dropping to 25%); the participants fail to grasp the large object in all tasks when wearing the device but using their own hand, despite successfully performing the front GRT 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’ remain 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 GRT, along with the mean difference between the two populations, are presented in Fig. 10. The normative population demonstrates 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 exhibit shorter completion times compared to the joystick and wrist angle control modes in normative subjects; this can be attributed to the fact that using the device requires additional time to operate fingers with fixed speeds, whereas bare hands...
Fig. 10. Results of the (a) completion time and (b) wrist travel distance of the GRT. 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).

can accomplish a grasp very quickly. In normative participants, unimanual grasping without a device exhibits the shortest wrist travel distance, while bimanual grasping displays 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 exhibit 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 front GRT, while none of the participants could perform the unassisted unimanual side GRT. On the other hand, the utilization of the Dorsal Grasper resulted in successful grasps across all participants during the ‘large object Side GRT’ 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 face mobility challenges that require them to spend more time rotating their bodies towards the object. Conversely, device-assisted grasping did result in the shortest travel distances. Although time is not significantly affected, the device enables 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). Notably, the differences in completion times and wrist travel distance exhibit a decreasing trend across the grasping methods, with unimanual, bimanual grasping, and device-assisted modes, in that order. While participants with SCI display substantial variability across grasping methods, the mean difference results, for both travel distance and completion time, suggest that performance in GRT using the device is approaching that of normative participants. However, the observed diminishing differences are also in part due to a worsening grasp performance with the device in the normative population.

3) Torso rotation: The results of torso rotations during the GRT are presented in Fig. 11. We defined the range of motion as the angular difference between the maximum and minimum angles during each GRT task. Due to kinematic constraints, during side GRT with bimanual grasping, both subject populations exhibit notably larger ranges of motion compared to front GRT. Among normative subjects, unimanual grasping consistently exhibits the least body rotation across all task configurations, even when comparing side GRT tasks to front GRT. Among SCI subjects, device-assisted modes often result in significantly lower torso rotation compared to modes without the device. Therefore, the device assisted modes consistently provide significant reductions in transverse and lateral compared with bimanual grasping, and sometimes unimanual grasping as well. While normative subjects tend to show larger ranges of motion with bimanual grasping than with unimanual grasping, SCI subjects during the ‘large object
Fig. 11. Torso rotation results during the GRT. (a) Three torso rotations and their sign convention. (b-c) Representative torso rotation during GRT 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 GRT. 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).

Front GRT task exhibit median values for unimanual grasping larger than those for bimanual grasping. For both populations, differences between the joystick and wrist angle control modes are not substantial, except for the ‘large object Side GRT’ task in flexion/extension from the SCI subjects.

The mean difference of the range of motions between SCI and normative subjects is shown at the bottom of Fig. 11c-e. In unimanual grasping, SCI subjects exhibit 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 side GRT, 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 are 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

All subjects expressed a preference for using the device over their own hand(s) for GRT tasks. 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, subjects S1, S2, and S4 rated the device a 4 out of 5, while subject S3 rated it 2.5 out of 5, with 0 being uncomfortable and 5 being very comfortable. Subject S4 mentioned that the weight of the device was the only complaint, and 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].” 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. However, they found the wrist angle mode easier to learn, with subject S1 commenting, “The wrist angle was more intuitive than the joystick.”
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 GRT data into five distinct phases: approach, grasp, transport, release, and return. We illustrate one subject performing the front GRT in Fig. 12. Following the hand’s approach to the start area, the subject extends the wrist to close the supernumerary fingers around the object, then transports it to the target area, releases the object, and finally returns 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 arrow) after the motor stopped, before starting the transport phase. This second wrist extension effort was observed in two subjects with SCI in the GRT with the larger object. From this observation, we hypothesize that some subjects can perceive and intuitively increase grasp security as needed while using the device.

![Fig. 12. Representative sensor readings from front GRT. Dotted lines show transitions between grasping phases: I. approach, II. grasp, III. transport, IV. release, and V. return.](image)

V. Discussion

For individuals with SCI, unimanual and bimanual grasping have complementary strengths and weaknesses. Unimanual grasping provides a larger graspable workspace (Fig. 8b) but is largely limited to small and light objects (Fig. 9). In contrast, bimanual grasping can handle larger and heavier objects but is limited to small and light objects (Fig. 9). In this work, we quantify the efficiency of the movement by tracking completion times and wrist travel distances (Fig. 10) and trunk movements (Fig. 11), comparing ‘no device’ to ‘device assisted’ test conditions. All three measures confirm that the Dorsal Grasper provides 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 find that these groups perform more similarly when using the device; while this is associated with improved performance in subjects with SCI, it also amplified by a reduction in performance by normative subjects.

One of the goals of the device is to enable supernumerary grasping for heavier and larger objects without limiting people from using tenodesis grasping for small, light objects. However, according to the results of the GRT, using tenodesis grasping under ‘Device unassisted’ shows decreased success rate compared to ‘No device’ (Fig. 9), specifically for S2 and S4. The added weight of the device requires 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, thus some individuals can still perform typical unimanual tenodesis grasping with the device on. Future work will explore device customization to reduce weight and minimize interference with tenodesis grasping across individual variability.

Both the joystick and wrist angle control modes of the device show similar results in terms of workspace and GRT performance. Despite this similarity, these control modes offer distinct functionalities tailored to different user requirements, with each appealing to SCI subjects for different applications. The joystick control mode allows 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 offers an intuitive approach, using wrist extension like in tenodesis grasp. One of the advantages of wrist angle mode over joystick mode is the liberation of the opposite hand; the left hand can 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 observe 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. Further study of user participation in such collaborative grasping is left to future work.

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 tables to be wheelchair inaccessible, highlighting the Dorsal Grasper’s important capability to expand the reachable workspace of users while avoiding the need to perform large torso movements. This 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.