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Assistive supernumerary grasping with the back of the hand

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***Abstract*— The Dorsal Grasper, an assistive wearable grasping device, incorporates supernumerary fingers and an artificial palm with the forearm and back of the hand, respectively. It enables power wrap grasping and adduction pinching with its V-shaped soft fingers. Designed with C6/C7 spinal cord injury in mind, it takes advantage of active wrist extension that remains in this population after injury. We propose that allowing the operator to actively participate in applying grasp forces on the object, using the back of the hand, enables intuitive, fast and reliable grasping relevant for the execution of activities of daily living. Functional grasping is tested in three normative subjects and a person with C6 SCI using the Grasp and Release Test. Results indicate that this device provides promising performance on a subset of objects that complements the existing compensatory strategies used by people with C6/C7 SCI. We find that the addition of the artificial palm is important for increasing maximum grip strength, by increasing contact friction and protecting the opisthenar.**

I. Introduction

Spinal cord injury affects an estimated 40 million people worldwide every year [1]. Cervical-level spinal cord injury (SCI) results in tetraplegia, or paraplegia, and can dramatically reduce a person's ability to perform common activities of daily living (ADL), e.g., manipulating and grasping objects in the home necessary for cooking, donning cloths, inserting a catheter, etc., ultimately leading to loss of independence. When surveyed, people with cervical SCI report that hand and arm use has the highest functional importance in terms of research prioritization for improving quality of life [2], ranking above pain relief and walking.

People with SCI at the C6/C7 cervical levels generally lose voluntary flexion of the wrist and fingers [3], however wrist extension typically remains [4]. Active wrist extension elicits passive thumb-to-forefinger and finger-to-palm flexion, called "tenodesis" [5], as demonstrated in Fig. 1. This flexion of the fingers enables passive tenodesis grasping [6], which is most effective for picking up light and small objects. However, tenodesis grasp is typically unsuitable for larger and heavier objects [7]. Empowering more dexterity with assistive devices, in this work through enabling power grasping, has the potential to improve psychosocial and economic outcomes after injury [8].

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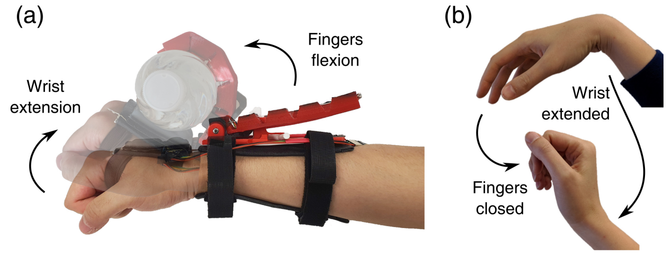

Fig. 1. (a) The Dorsal Grasper includes a set of soft flexible fingers and an artificial palm on the dorsal part of the hand. Here, a water-bottle is grasped using both operator wrist extension and artificial finger flexion. (b) A tenodesis demonstration shows active wrist extension elicits passive finger flexion, from [11].

A. Related Work

Several assistive devices have been designed to support hand function for people with cervical SCI. One commonly prescribed device is the wrist-driven orthosis (WDO), which uses a mechanical linkage to assist tenodesis grasping [9]–[11]. Despite being body-powered and consequently lightweight, physically resilient and low cost, patients tend to abandon WDOs over time as they get used to unassisted tenodesis and opt to use a set of more specialized tools [12]. Constraining the hand to always use tenodesis grasping is problematic for the full set tasks required for ADL [13]. There are a wide number motor-articulated investigational devices [14], though few are commercially available. Recently, a number of new devices based on soft materials have received attention due to the potential benefits of creating compliant and light-weight structures, such as fabric-based actuators [15], [16] and soft linkages [17]–[19].

Instead of assisting the person to move their own fingers, another option is to add extra-fingers to the hand. Wu and Asada (2015) introduced a supernumerary robotic (SR) finger to perform "hold-and-manipulate" tasks for stroke survivors and other patients with limb impairments [20]; extra fingers are mounted on a wrist brace and primarily oppose the palm. Hussain, et al. (2016) separately reported on a soft-sixth finger for grasp compensation in chronic stroke patients [21]; the soft-sixth finger is worn like a bracelet and largely opposes the radial side of the hand during grasping. We explore how this supernumery finger concept may be adapted to grasping with the back of the hand.

B. Overview

We are expanding the concept of supernumerary fingers, taking into account the pathology of people with C6/C7 SCI. We expect that adding a set of supernumerary fingers on the opisthenar, or the back of the hand, can provide

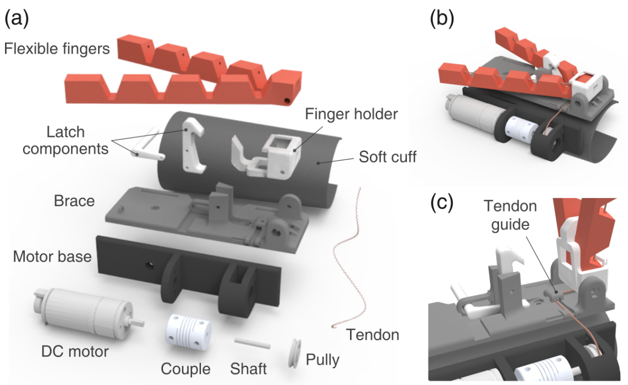

Fig. 2. CAD images of the Dorsal Grasper: (a) exploded, (b) assembled, and (c) tendon routing details.

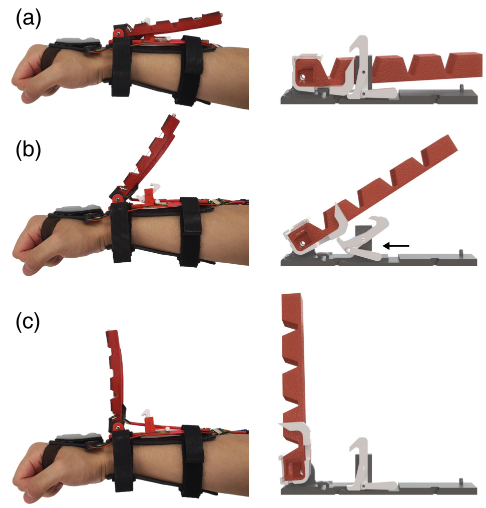

Fig. 3. Deployment from "storage" (a) to "ready-to-grasp" (c). (a) The finger housing is held down with a releasable latch. (b) The user can deploy the fingers to the ready stage by pushing the positioning bar with his or her opposite hand. The base of the latch pushes the fingers forward towards the hand. (c) The Dorsal Grasper reaches its "ready" stage once the motor pulls the finger tendon taut in the upright position.

grasping on larger objects in a way that takes advantage of active wrist extension for intuitive and fast operation (Fig. 1). Importantly, by using the dorsal side of the hand, the device does not impede common use of the hand for other purposes such as palmar tenodesis grasping or the use of specialized tools. Often individuals with cervical SCI can extend the wrist, e.g., subjects with C5/C6 SCI can extend the wrist with approximately 1 N of force [22]. Thus, we expect dorsal grasps to be relatively gentle compared with normative power grasping.

Section II describes how the supernumerary fingers are constructed and how they function. These fingers are controlled via a joystick for initial testing with human subjects. The palm plays a role in human and animal grasping [23], [24], while the skin on the back of the hand is thin, highly elastic and has little underlying tissue [25]. The opisthenar thus produces less friction and contact area with objects compared with the palm, and an artificial supernumerary palm is added to the back of the hand. We perform three discrete experimental tests with this system, described in Section III: the grasping of different sized boxes, maximum grasp force, and a modified Grasp and Release Test. As described in Section IV, we find that the Dorsal Grasper enables both adduction pinching and palmar grasping, and that human subjects change grasp strategy depending on the object. The artificial palm, combined with active wrist extension, increases power grasp strength. Trials performed by a person with SCI indicate this device holds the potential to support the execution of ADLs, discussed in Section V.

II. The Dorsal Grasper

The Dorsal Grasper is a compliant wearable device capable of grasping objects of various shapes and sizes. The mechanism is made of 3D printed plastic (PLA) and rubber (Ninjaflex) parts and a thermoplastic (Worbla sheet, TAP Plastics) cuff that provides a lightweight and flexible interface with the forearm. As shown in Fig. 2, the tendon-driven flexible fingers fit into a hinged finger-holder. The fingers rest two states: (1) the storage-stage, when the fingers lay back flat against the forearm, not in use, and (2) the ready-stage, when the fingers sit upright perpendicular to the forearm. A releasable latch holds the fingers in the storage-state, shown in Fig. 3. When grasping, finger flexion is driven by a 0.4-mm-diameter rope (PE Braided line) on a 12 mm diameter winch with a DC motor (12V with a 156:1 metal gearbox). The brace and motor base are both fastened onto the soft cuff and the tendon is routed over a polished fixed pulley between these two elements.

A. Soft Tendon-driven Finger

The soft tendon-driven fingers are 130 mm in length and the angle between the two fingers is 35.5 degrees (Fig. 2 and 4), which provides a balance between finger spread, for resisting object moments, and portability. V-shaped fingers were previously introduced for supernumerary applications in [26], [27]. Each finger consists of four equally sized phalanges with 4 mm gaps in between. A 2 mm diameter hole in the upper part of each phalanx (11.5 mm from the back of the finger) allows the tendon to route through each then terminates at the distal tip. The thickness of each inter-phalangeal flexure linearly increases from 2.5 to 4 mm, from proximal to distal, to generate a slight base-to-tip curling order. In order to increase the frictional coefficient between an object and the finger, rubber (Multipurpose rubber, Plasti-Dip) is coated onto the surface of each phalanx.

The V-shaped finger configuration in the Dorsal Grasper enables two separate grasp types: power palmar grasping (Fig. 1a) and gentle adduction pinching (Fig. 5c). In palmar grasping, the fingers press the object into the back of the person's hand. Alternatively, the user can pinch small objects as the fingers wrap inward towards the finger holder, approximating finger adduction. These two grasp classifications are qualitatively similar to grasping strategies of the human hand, defined in grasp taxonomies [28], [29] and demonstrated in Fig. 5a-b.

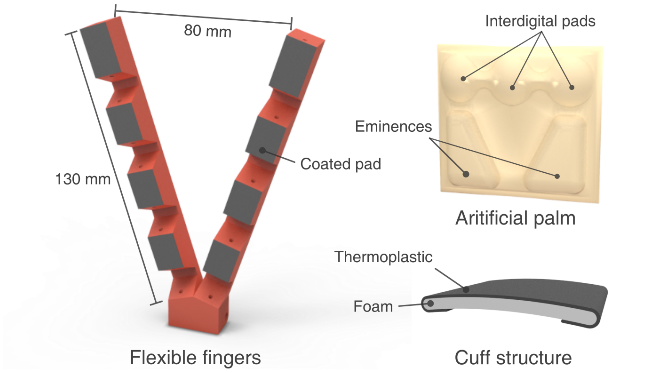

Fig. 4. CAD images of the flexible fingers, artificial palm, and structure of the cuffs.

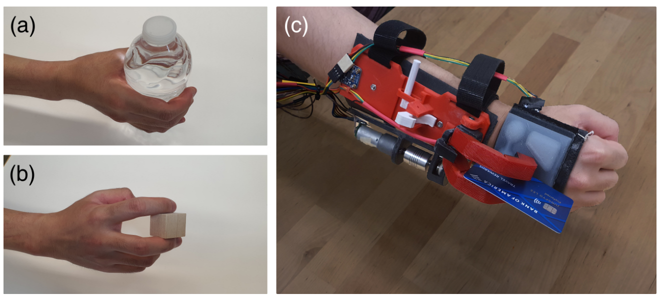

Fig. 5. (a) Palmar grasping and (b) adduction pinching of the human hand. (c) Abduction pinching a credit card with the Dorsal Grasper.

B. Artificial Palm

This device uses the back of the hand as a grasping surface. In the human hand, the skin of the opisthenar is relatively thin and fragile as compared to the palm, that regularly resists scratching and bruising. In contrast to the palmar surface, the skin of the opisthenar is also highly pliable and hairy [25]. In order to increase comfort, strength and friction during dorsal grasping, an artificial palm is attached to the opithenar using an elastic band. The palm is fabricated with a silicone rubber (Dragon Skin 10) molded onto Velcro[1] using a 3D printed negative. This artificial palm interfaces with the body using a soft cuff made of thermoplastic shaped to fit the back of the hand. The compliant silicone pad is intended to conforms to various object shapes during grasping. The concave shape of the artificial palm (Fig. 4) is roughly inspired by the structure of the human hand, which has three interdigital pads positioned in between the thenar and hypothenar eminences on its palm [30].

C. Attachment to the body

In order to provide reliable grasping, the forearm attachment must be secure on the body, yet comfortable. The thermoplastic forearm cuff wraps around the ulna of the arm, allowing it to resist torsional forces. We use soft foam on the inside of the thermoplastic forearm cuff (Fig. 4) to protect the skin and distribute contact pressure. The flexible property of the thermoplastic allows it to fit onto forearms of various sizes. Velcro loops allow the wearer to fasten the device tightly to his or her own forearm. While the cuff can resist the forces due to grasping and lifting, and stays stationary on the skin, there is some motion of the device due to the soft nature of the underlying tissue of the forearm. The cuff for the artificial palm is fabricated in the same way as the forearm cuff. The elastic band attached to the artificial palm wraps around the person's palm and holds it in place on the back of the hand, visible in Fig. 3.

[1]We find the loop side of the Velcro provides strong bonding with the silicone, while the hook side of the Velcro de-laminates easily and is not recommended.

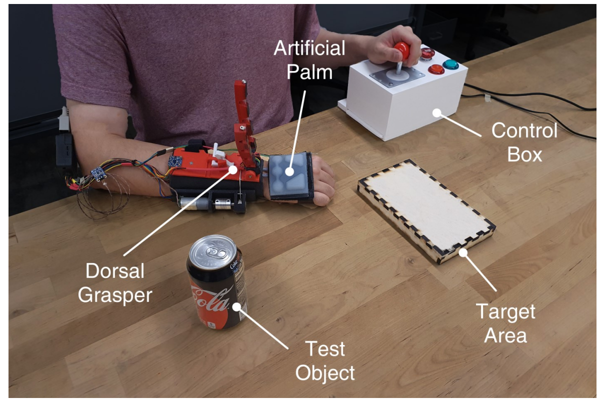

Fig. 6. The experimental setup for the block test and the Grasp and Release Test, including the control box, object starting location and target area.

TABLE I
OBJECTS SPECIFICATION OF THE GRASP AND RELEASE TEST

Test object	Object weight (N)	Object size (cm)
Can	3.48	12.3 x 6.6 (dia)
Videotape	1.28	19.3 x 10.9 x 2.8
Paperweight	2.32	5 x 1.4 (th)
Block	0.102	2.5 x 2.5 x 2.5
Peg	0.041	8.0 x 0.6 (dia)

D. Control interface and data acquisition

Grasping commands are input by the wearer using their opposite hand through a control box fixed to the test-bench. The box is comprised of: i) a large arcade joystick, ii) an emergency stop button, iii) two LED indicators, and iv) the motor control electronics (Fig. 6). The left and right toggling of the joystick triggers grasping (finger flexion) and opening (finger extension) motions. A motor encoder measures finger actuation while a distance sensor, installed in the finger holder, measures the distance between the base of the finger and the object. An accelerometer on the artificial palm observes the motions of the hand. The wires for these on-board sensors are routed to the control box, but these signals are used only for data recording and not yet as inputs for control behavior.

III. EXPERIMENTAL METHODS

We test the performance of the Dorsal Grasper under the University of California at Berkeley IRB-approved human subject protocol #2019-07-12348.

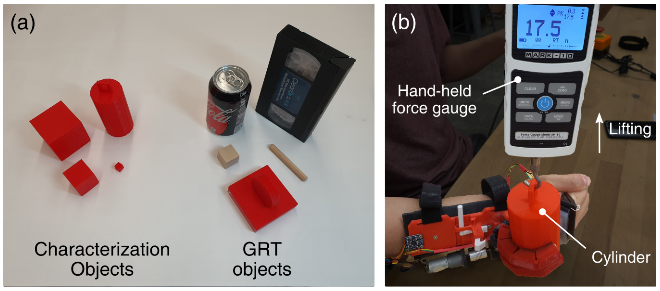

Fig. 7. (a) Experimental objects for Dorsal Grasper testing include a cylinder with 50 mm diameter, cubes of 10, 35, and 60 mm edge length, and objects replicating the standard Grasp and Release Test kit. (b) The strength test setup uses a handheld force gauge to pull the object out of the grip.

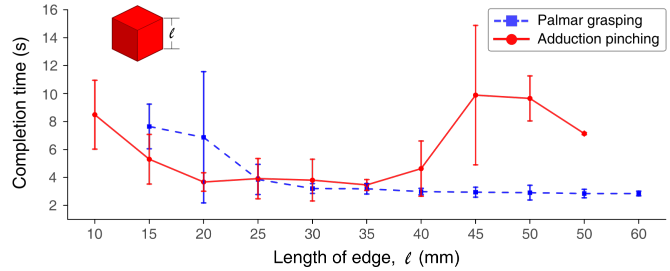

Fig. 8. Comparison of completion time between palmar grasping and adduction pinching with the Dorsal Grasper on cubes of various sizes. Data is presented as the mean ± s.d. across all trials with two normative subjects.

A. Grasping type comparison: block test

Anticipating that the ease of performing power grasping and adduction pinching with the Dorsal Grasper might change with object size, we prepare 3D printed cubes with a variety of sizes, from 10 to 60 mm length scale (Fig. 7a). Two normative subjects are asked to pick up the cube from an initial location on the table, 40 cm from the front edge of the table and in-line with person's shoulder. They then place it on a target location in-line with the opposite shoulder shown in Fig. 6. The time to complete the maneuver is recorded for both grasp methods over all cube sizes for 5 trials each. Since the experiment is conducted with light-weight cubes, results may vary if conducted with heavier objects.

B. Maximum palmar grip strength

The artificial palm plays a role in both shielding the skin and increasing friction. Thus, we test the effect of the palm on the lift strength of the device. Three normative subjects are asked to grasp cylindrical objects then a hand-held force gauge (Mark-10 M4-50, MSI Viking) is used to pull the object out along the cylinder's axis, perpendicular to the finger plane of motion. The peak force needed to initiate any slip on the surface of either the artificial palm or the finger is recorded (Fig. 7b). Cylinders with 40, 50, and 60 mm diameters are each tested 10 times, both with and without the artificial palm. This entire set of trials is conducted (1) with the subject applying maximum wrist extension and (2) holding the wrist steady in a neutral pose.

C. The Grasp and Release Test

We utilize a modified Grasp and Release Test (GRT), which is specifically designed to quantitatively measure the grasping abilities in tetraplegic patients [31], to measure versatility and reliability of the Dorsal Grasper. Participants are asked to grasp, move, and release different objects, as shown in Fig. 6. If the subject completes the goal for a given object within 30-seconds, it is considered a success, otherwise it is considered a failure. We use five objects from the original GRT, pictured in Fig. 7a, excluding the fork because the size does not fit the designed device. Object specifications are listed in Table I. The objects are presented in the order: can, videotape, weight, block, and peg. The researcher first places the object on the start area in a random orientation. Then the subject is video recorded and timed during their attempts. For the block and peg, the object can be dropped into the target area with any orientation. For the can, paperweight, and videotape, the object must be placed in an upright orientation on the target area to be counted as a success. The participant is allowed to attempt the tasks as many times as possible within the 30-second time. Data is collected from four human subjects: two normative subjects are accustomed to using the device while one normative subject and one subject with C6 SCI are not familiar with using the device. Subjects unfamiliar with the device perform 10-minutes of grasping practice prior to data collection.

IV. Results and Discussion

A. Block test

Mean and standard deviation data from the block test is shown in Fig. 8, and indicates that the two different grasp types – palmar and adduction – provide different benefits based on object size. The 10 mm cube was too small to conduct the task with palmar grasping and the 60 mm cube was too large for adduction pinching, thus these data-points are excluded.

For cubes of size 25 mm to 35 mm, palmar grasping and adduction pinching have similar task completion times. For the small 15 mm and 20 mm cubes, palmar grasping requires more time to complete (7.6 ± 1.6 s & 6.9 ± 4.7 s respectively) than adduction pinching (5.3 ± 1.8 s & 3.7 ± 0.7 s respectively). Difficulty in performing palmar grasps on small objects occurs when the object is smaller than the fingers can curl; the object must be carefully pinched between the fingertip and the palm. Adduction pinching also becomes increasingly difficult as object size decreases because of limited adduction range of motion. For objects larger than 20 mm, palmar grasp completion times decrease monotonically from 25 mm (3.9 ± 1.1 s) to 60 mm (2.8 ± 0.2 s), and standard deviation diminishes. Palmar grasping outperforms adduction pinching for 40 mm cubes (4.6 ± 2.0 s) and bigger. Difficulty in performing adduction pinch with large objects emerges from limited adduction range of motion and curling behavior; when the finger starts to flex, the gap between the adjacent fingers closes rapidly and requires careful control to succeed.

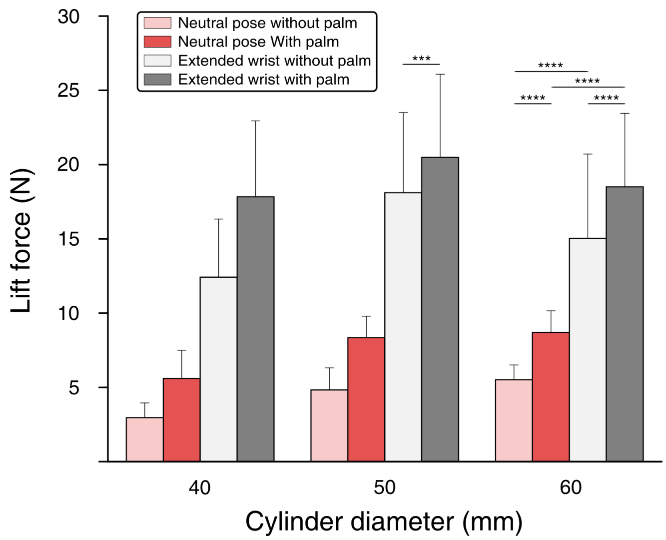

Fig. 9. The lift force of the Dorsal Grasper both with and without the artificial palm and wrist extension over varying cylinder diameters. Statistical significance for all paired t-test comparisons for each object are ****$p < 0.0001$, as shown only for 60 mm. The only exception is the comparison between extended wrist with and without the palm with the 50 mm cylinder, which is ***$p < 0.001$. Data are presented as the mean ± s.d. (n = 30, 3 normative subjects for 10 trials each).

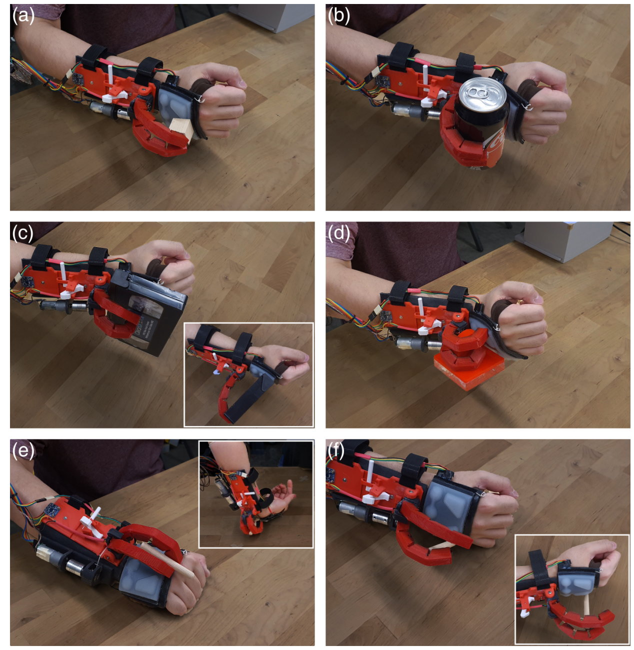

Fig. 10. The Dorsal Grasper is used to perform the Grasp and Release Test on five objects: (a) a block, (b) a can, (c) a videotape, showing an inset image of an alternative object orientation, (d) a paperweight, and (e)-(f) a peg. (e) Pinching a peg is possible with finger-adduction and the inset shows the body pose of one subject's pinching strategy, where they place their opisthenar on the table with their fingers pointing toward their trunk. (f) Grasping a peg is also possible with a single finger against the palm.

B. Grip strength

As shown in Fig. 9, there is a significant positive effect on lifting force with both the use of the artificial palm and wrist extension. For all three object diameters, holding the wrist neutral without the artificial palm is weakest while extending the wrist with the artificial palm is strongest. During trial observations, initial slip occurred at either the back of the hand or the fingers. One subject noted discomfort on the back of the hand when extending the wrist without wearing the artificial palm, caused by the fingertips of the device pushing into the dorsal skin, and this may have caused them to limit their wrist extension force. Regardless of whether the benefit is due extension strength or friction coefficient, wearing the artificial palm allows the operator to achieve greater grasp lifting forces. The difference between neutral pose and extended wrist trials indicate that an operator can actively moderate their maximum lift force using wrist extension, even after the fingers are fully actuated.

There appears to be a minor trend with object size. Cases that extend the wrist are maximized for the 50 mm cylinder, for both the bare hand (18.11 ± 5.39 N) and artificial palm (20.49 ± 5.58 N). Whereas, the results from the neutral wrist pose show gradual increases of lift force with cylinder size. This is likely caused by changes in soft finger pose with wrist pose.

C. The Grasp and Release Test

As shown in Fig. 10, the Dorsal Grasper enables grasping of all 5 GRT objects tested. Success rates out of 9 trials for each of the three normative subjects and 5 trials for the subject with C6 SCI are listed in Table II. Examples of successful trials performed by the subject with SCI are included in the paper video extension. The soda can (b) and the paperweight (d) are grasped in approximately the same palmar method every time. One subject reported that the paperweight required maximum wrist strength due to its heavy weight and particular shape. For the videotape, subjects vary their palmar grasp orientation, shown in (c). The block is typically gripped in a palmar fashion, even though adduction pinch is possible, described in Sec. IV-A. The peg has the largest grasp strategy variability. While most successful trials are performed using adduction pinching (e), a couple successful trials are achieved using a palmar pinch with one finger (f). Only one subject consistently succeeds at the peg tasks (8/9 success rate) by orienting the hand as pictured in (e). Task failures occur if: (1) the paperweight is too heavy to lift, (2) the videotape or soda can is accidentally knocked over or dropped so it is no longer upright and isn't re-grasped, or (3) it takes too long to secure the peg in either a palmar or adduction grip. Completion times for each object across all subjects and successful trials are reported in Fig. 11. The subject with C6 SCI takes longer on average to complete tasks, except with the block. Observed grasping

TABLE II
SUCCESS RATE OF THE GRASP AND RELEASE TEST

Subject number	Can	Videotape	Paperweight	Block	Peg
Subject 1	7/9	8/9	9/9	9/9	0/9
Subject 2	9/9	8/9	9/9	9/9	2/9
Subject 3	9/9	9/9	8/9	9/9	8/9
SCI subject	5/5	5/5	4/5	5/5	2/5

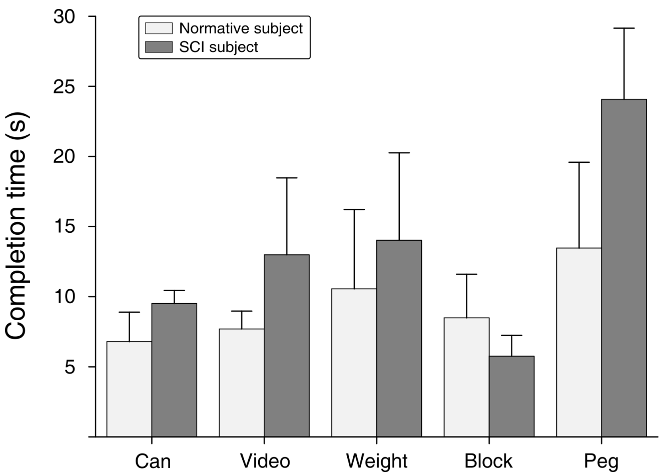

Fig. 11. Completion times for successful trials in the modified Grasp and Release Test, showing the difference between the three normative subjects and a subject with C6 SCI. Data are presented as the mean ± s.d.

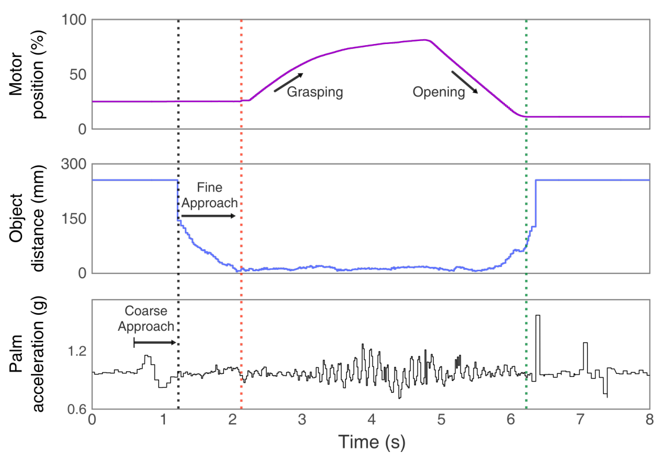

Fig. 12. Representative real time recorded data during the execution of the Grasp and Release Test with the can. The black dotted line indicates the start time of fine approach. The red and green dotted lines indicate the start and end time point of the motor operation, respectively.

strategies and grasp success rates for the subject with SCI are otherwise similar to the normative subjects.

Recordings from the motor encoder, object distance sensor and palm accelerometer are plotted in Fig. 12 for a single representative grasp trial with the soda can. We divide the GRT trial into multiple steps: a coarse approach to the object, a fine approach, grasping and opening. During the coarse approach, the accelerometer captures the typical reaching-to-grasp acceleration and deceleration curves [32], [33]. During fine approach, the distance between the device and object closes gradually. The user then grasps and releases the object by operating the motor to flex the finger. Fluctuation of the acceleration during grasping and opening phases may occur from the action of the person or vibrations of the motor. We aim to use these types of on-board readings to automate device behavior in future work, in lieu of the joystick.

Fig. 13. The subject with SCI picks up a water-bottle and pours water into a mug without spilling.

D. ADL demonstration

To test the utility of the Dorsal Grasper in a more realistic ADL, the subject with SCI is asked to pour water from a 500 ml bottle into a mug (Fig. 13). The subject performs the task without spilling water, and a recording is included in the video extension associated with this paper. The extension also demonstrates the grasping of various ADL objects by a normative subject; it shows that the device can rapidly grasp different shapes.

V. Conclusion

The Dorsal Grasper enables operators to grasp objects with the opisthenar, using a set of supernumerary flexible fingers combined with an artificial palm. For strong palmar grasping, it benefits from extension of the wrist, which is commonly maintained in people after C6/C7 SCI. In addition to palmar grasping, adduction pinching exploits the V-shape of the fingers that adduct while curling. In part because this device empowers a number of different grasping strategies, preliminary data suggests that each person may demonstrate different preferences and performance when using it. Regardless, it provides intuitive operation for both experienced and inexperienced users, and both people with and without SCI.

We envision the Dorsal Grasper could serve as a candidate tool for people with SCI in performing activities of daily living, especially for larger objects that are difficult to secure in a tenodesis grasp. Because the device requires wrist extension to get the highest gripping forces, it may produce wrist fatigue with prolonged use, or encourage the strengthening extensor muscles. Future work should expand subject sample size and measure muscle activation over longer periods during ADL. Prior supernumerary grasping works monitor muscle activation with EMG sensors [26] and finger movements with stretch sensors [34]. Future work will also incorporate wearable control input methods, by replacing the table-mounted controller box for more streamlined on-board inputs.

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