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Authors

Chang, Erin Y

McPherson, Andrew IW

Adolf, Ryan C

et al.

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Modulating Wrist-Hand Kinematics in Motorized Assisted Grasping with C5-6 Spinal Cord Injury

Erin Y. Chang*, Andrew I. W. McPherson, Ryan C. Adolf, Yuri Gloumakov, and Hannah S. Stuart*

***Abstract*—Loss of hand function severely impacts the independence of people with spinal cord injuries (SCI) between C5 and C7. To achieve limited grasps or strengthen grip around small objects, these individuals commonly employ a compensatory technique to passively induce finger flexion by extending their wrist. Passive body-powered devices using wrist-driven actuation have been developed to assist this function, in addition to advancements in active robotic devices aimed at finger articulation for dexterous manipulation. Nevertheless, neither passive nor active devices see wide adoption and retention in the long-term. Here we present an unconventional system for combining aspects of both passive and active actuation and show that actively modulating the relationship between passive wrist and finger movement can impact both performance and kinematic metrics of upper body compensation. This study comprises six unique case studies of individuals with C5-6 SCI because morphology and response can vary widely across this population. While only some individuals' performance improved with the shared system over passive-only operation, all six participants stated that they preferred the shared system, regarding added motorization with a sense of trust and embodiment. This outcome motivates the ongoing study of how motors can alter body kinematics to augment body-power without replacing it.**

***Index Terms*—physically assistive devices, exoskeletons, wearable robotics, spinal cord injury**

I. Introduction

TETRAPLEGIA due to traumatic cervical spinal cord injury (SCI) affects up to 225,000 people in the United States alone [1]. This condition impairs hand and arm functionality, which limits a person's ability to perform activities of daily living (ADLs) and their personal independence. Surveys indicate that people with tetraplegia and SCI highly prioritize hand and arm function restoration, as it can improve quality of life [2], [3]. Furthermore, regaining upper limb function remains their top priority regardless of the number of years since the injury was sustained [4].

Radial wrist extensor muscles (extensor carpi radialis longus and brevis) retain some innervation at injuries about the C6 and C7 nerve roots [5], which can allow individuals to learn alternative methods of prehensile movement. Tenodesis grasp is achieved by extending the wrist, which passively shortens the flexor muscles in the thumb and fingers to gently close the paralyzed hand. SCI at these low cervical levels often impacts wrist flexor muscles [5], [6], so individuals typically use gravity to reopen the hand.[1] This technique can achieve either a pinch grip (thumb and finger tip contact) or lateral key grip (thumb and lateral finger contact) [7]. Typically, tenodesis grasp generates weak forces often insufficient for the manipulation of most day-to-day objects [8]–[10].

Functional assistive orthotics offer a noninvasive method to improve hand function. Passive body-powered devices map user input movement directly to mechanical device actuation, which offers a high level of human control, but results in an inherent force-motion tradeoff. This may result in soreness and fatigue, as has been shown with body-powered prosthesis use [11]–[13]. In contrast, active robotic devices use elements like electrical components to actuate the user's paralyzed appendages, which alleviate issues of body load, but separates user input from device actuation. This may reduce incidental feedback between the device and operator and can produce operational lags [14].[2] Researchers have developed a number of both passive and active assistive orthotic devices to improve hand dexterity, as reviewed in [16], [17], however, few have left the research stage and been broadly adopted. In this work, we conduct six case studies on individuals with SCI to explore how combining passive and active components in a human-robot shared grasp system can address the limitations of each device control method alone, and bridge the adoption gap.

Since people with C5-7 SCI are familiar with wrist extension as a passive grasping mechanism, the flexor hinge hand or the wrist-driven orthosis (WDO) has remained on the market as a passive body-powered solution since its development in the 1950s-1960s [18], [19]. Mechanical linkages in the WDO couple wrist extension motion to a three-jaw chuck pinch grasp,[3] thereby adding structure and support to an otherwise weak tenodesis grasp. Similar designs continue to be manufactured by companies like Becker Orthopedic [21] and Jaeco Orthopedic [22], however, the WDO's ubiquity among individuals with SCI and longitudinal use appears to decrease over time [23]–[25]. Despite its sparse acceptance, the benefit of the device remains promising and recent research has sought to iterate on the WDO design to improve its practicality and value for modern day use, like through modified open source and adjustable designs that can easily be 3D printed [26], [27].

E.Y. Chang, A.I.W. McPherson, R.C. Adolf, Y. Gloumakov, and H.S. Stuart are with the Embodied Dexterity Group, Dept. of Mechanical Engineering, University of California Berkeley, Berkeley, CA, USA.

* Corresponding authors (erin.chang@berkeley.edu; hstuart@berkeley.edu)

This work has a supplemental video associated with it.

[1] The resulting distance between the fingers and thumb may remain small, depending on muscle and tendon tightness.

[2] This lost feedback might otherwise have contributed to the user's sense of extended physiological proprioception (EPP) [15], thought to enhance device embodiment and acceptance [14].

[3] WDOs may encourage this particular grasping technique because positioning the thumb and fingers in opposition accounts for grasp postures related to around 80% of prehensile grasps [20].

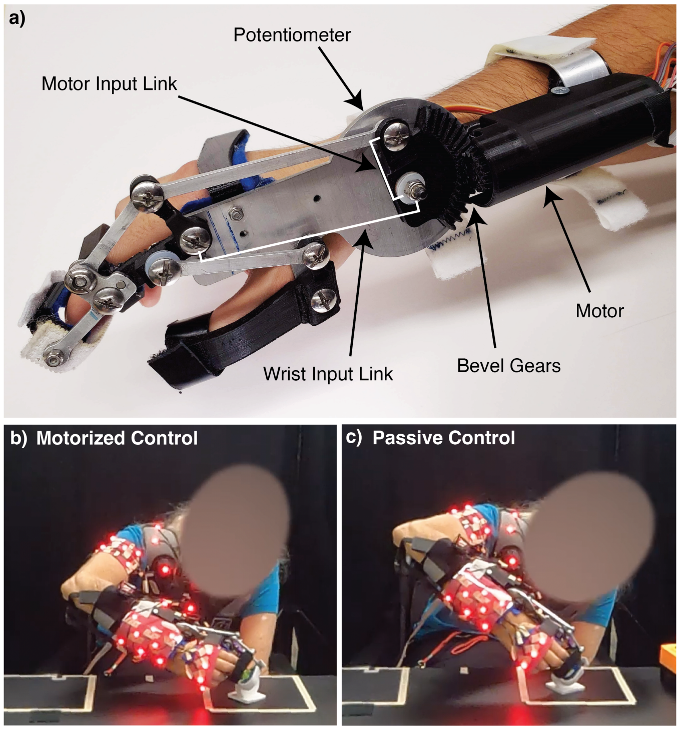

Fig. 1. a) Motorized Wrist-Driven Orthosis (MWDO), from [28]. When using *motorized* control, the potentiometer measures wrist angle via wrist input link position and the motor correspondingly drives the bevel gears to rotate the position of the motor input link. b) A participant with SCI operating the MWDO with *motorized* control. c) The participant operating the MWDO with *passive* control (motor off).

A. Related prior work

Pictured in Fig. 1a, we previously introduced the design of the Motorized Wrist-Driven Orthosis (MWDO), a system that shares elements from both traditionally passive and active devices [28]. The MWDO replicates the functionality of a body-powered WDO in the *passive* control state (with the motor inactive) and additionally offers a "shared" or *motorized* option of robotic-assisted wrist-driven grasping by articulating one link with a motor. One subject performed an initial successful demonstration of grasping and manipulating a round door knob, a set of keys, and a pen in the *motorized* control state and we showed how the motor can be used to selectively decouple wrist and gripper motion [28].

In our first follow-up work, we adapted the MWDO to create the Tenodesis Grasp Emulator (TGE) for a study of the tenodesis grasp motion and the two control states on normative subjects without SCI [29]. Since loss of distal motor function increases compensation during reaching and grasping activities [30]–[32], we assessed upper body kinematics through the range of motion (ROM) of upper body angles and the length of Cartesian paths traveled by the torso and upper-limb segments during grasping tasks. Results indicated that coupling the hand and wrist movements (such as in tenodesis grasp) induced statistically significant compensatory movements compared to decoupled movements, and decreasing the necessary wrist movement by including motorized grasp assistance can reduce such compensation, depending on object and task.

B. Overview

In the present work, we investigate how the unique use of a motor to modulate wrist-hand kinematics in the MWDO (without directly augmenting grasp force) can impact the performance and perceptions of people with SCI. We hypothesize that reducing input body motion can benefit some individuals by improving dexterity and reducing unnecessary body compensation. In Section II, we perform a new kinematic analysis of the MWDO's mechanical design. Then in Section III, we describe a comprehensive usability study of the device on six subjects with SCI (Fig. 1b,c), which combines functional, biomechanical, and qualitative evaluation methods. Section IV details our findings and the outcomes of the experiment, and we discuss their implications, our study's limitations, and future works in Sections V and VI.

II. The Motorized Wrist-Driven Orthosis

The WDO aims to support and augment the tenodesis pinch grasp through rigid supports to combat laxity of the fingers and thumb, and added mechanical advantage due to the four-bar linkage mechanism. Motorizing the movement of one link then allows the resulting MWDO to contribute to grasping actuation along with the user's wrist extension. Here we present and assess the kinematics of the MWDO's mechanical design to understand the role of wrist and motor force on grasp strength. Wrist extensor strength and ROM may vary between individuals and motor selection must also trade-off strength with speed and weight.

A. Kinematic Analysis

The mechanical linkage structure of the MWDO is pictured in Fig. 2a. The device structure comprises multiple four-bar linkages, arranged such that applied wrist torque (τ_{wrist}) by the wearer in extension closes the thumb and fingers together to generate grasp force (F_{grasp}) on an object (Fig. 2b). Similarly, $-\tau_{wrist}$ in flexion moves the thumb and fingers in opposite directions to open the hand. For this analysis, we constrain the distal four-bar linkage and distal-most finger support to move as a rigid component (region outlined by D_M, M, and F_T in Fig. 2), simulating grasps where contact with the object occurs between the tips of the fingers (F_T) and thumb (T_T), as performed in Sec. III-B.

Since stable grasping occurs at static equilibrium and only two external torques are applied to the system, the stall torque of the motor (τ_{motor}) directly resists the input torque from the user (τ_{wrist}) such that zero net torque acts on the system. This is how the wearer is able to feel the forces applied at the grasp. There is a linear relationship between F_{grasp} and τ_{wrist}. The slope of this relationship depends on the linkage orientation angle (β), which is determined by the distance between the tips of the fingers and thumb during grasping, or the grasp aperture ($\overline{F_T T_T}$). A given β configuration can occur at different wrist orientations (α), depending on the motor's orientation (γ). Note that F_{grasp} for a given τ_{wrist} remains constant whether the MWDO is controlled passively or with motor assistance (Fig. 2c,d). In other words, we are only using the motor as a way to alter the relationship between β and α,

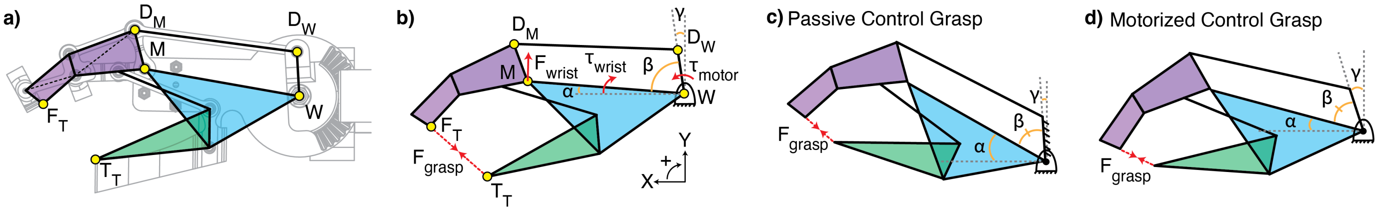

Fig. 2. a) Schematic of MWDO mechanism. Shaded regions represent rigid bodies for analysis. b) Force and torques for MWDO actuation. Variables are defined in the main text. c) Example of grasping in the *passive* control state, requiring a larger wrist extension angle, α, when compared to d) grasping in the *motorized* control state to achieve the same grasp aperture. β remains constant regardless of control state when grasping objects of the same size.

but do not alter mechanical advantage nor directly enhance grasp force with this actuator.

We define the mechanical advantage provided by the MWDO as:

$$MA = \frac{F_{grasp}}{F_{wrist}} \quad (1)$$

where F_{wrist} is the user-applied force during wrist extension at the metacarpophalangeal joint (M), normal to the dorsal plane of the hand ($\overline{MW}$), such that τ_{wrist} is the product of F_{wrist} and $\overline{MW}$. In Fig. 3, we show how mechanical advantage varies over a range of grasp apertures. At small apertures, and thus small β, we observe a non-monotonic mechanical advantage, with a local minimum. We conversely see that larger grasp apertures, which correspond to larger objects, yield greater mechanical advantage (Fig. 3).

In our prior work, subjects with normative hand function wore the TGE and performed grasping activities on objects with diameters of 14 mm and 60 mm [29]. According to Fig. 3, these grasp apertures would result in mechanical advantage of approximately 0.72 and 0.90, respectively. Initially, the same two object sizes were selected for the study detailed in the present work, however, none of the subjects with SCI could achieve a sufficiently large grasp aperture to place the larger object within the hand while wearing the MWDO. Therefore, the people in this study only operate the device in the low MA range. While the mechanical advantage generated by the MWDO linkage system often falls below 1 for most grasp apertures, it is comparable to other wrist-driven systems [9]; likely, low MA values are selected in WDO devices such that less wrist ROM is required to operate it. Regardless, since individuals with SCI performing tenodesis grasp without an assistive device typically generate negligible force [9], [10], the MWDO appreciably augments grasp strength. Changing the lengths of the moment arms within this system could enable a larger ratio of finger movement to wrist movement for grasping larger objects and further increase the MWDO's mechanical advantage for the user, if desired.

B. Device Actuation

In this work, we assess two control modes of the MWDO: *passive* control and *motorized* control. During *passive* control, the position of motor input link $\overline{WD_W}$ remains fixed (and thus γ remains fixed) and the device behaves like a typical body-powered WDO, using more extreme wrist angles represented by large α to move the fingers and thumb, as shown in Fig. 2c. When operating the device with *motorized* control,

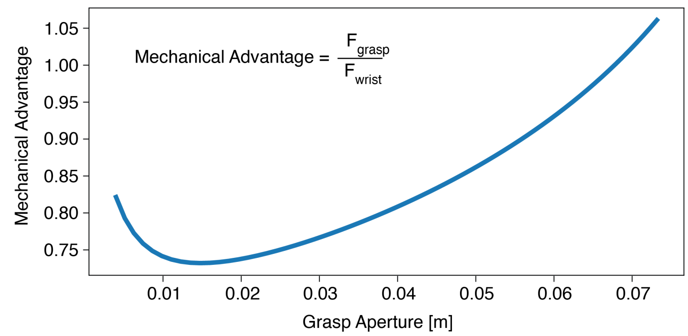

Fig. 3. Relative mechanical advantage generated by the MWDO at varying grasp apertures ($\overline{F_T T_T}$). $\overline{F_T T_T}$ is proportional to β.

the user still uses wrist movement to actuate the device, but now the motor provides bidirectional assistance by rotating $\overline{WD_W}$ about the fixed point W. $\overline{WD_W}$ rotates in the opposite direction of the wrist input link $\overline{MW}$, such that wrist angle α and motor input link angle γ are always equivalent. This relationship between the user's wrist movement and device's motor input results in a smaller α (compared to *passive* control) required to move the fingers and thumb, as shown in Fig. 2d, yet MA and F_{wrist} needed to grasp the object remain unchanged. Thus, the motor only contributes to the grasping action by reducing the user's required wrist movement. Altering this relationship between α and γ can also change the ratio of finger movement to wrist movement to assist with opening the hand in users with SCI, who have limited voluntary flexion.

To achieve this motorized control, a soft rotary potentiometer (Spectra Symbol SP-R-0046-353-103-3%-RH) measures the user's wrist position, then a moving average filter is applied before mapping this value to the corresponding motor position. When the user moves their wrist, the motor assists device actuation through bevel gears with a 3:1 ratio that rotate $\overline{WD_W}$ and we reduce angle error by implementing PI control.

C. Biomechanical Design Considerations

Users may perceive differences in exertion during operation of each control scheme, since ROM has been linked to perceived exertion. Researchers found that in the fully extended wrist posture, normative adult males could only achieve 30% of their peak wrist extension moment, indicating that joint position can impact the moment-generating capacity of the muscle [33]. At the larger wrist extension angles, like those required to passively control a WDO, wrist extensors may exhibit active insufficiency, or limited contraction, and generate smaller forces due to shortened muscle lengths. For individuals with SCI, maximum extension moments decrease even more so [9], likely due to lack of functional supporting musculature. Therefore, we expect that altering the wrist-hand kinematics by reducing the required ROM needed to operate a wrist-driven device can benefit this population.

Since the magnitudes of τ_{motor} and τ_{wrist} are equivalent during MWDO grasps, as found in Sec. II-A, the maximum F_{grasp} will be determined by the weaker of the two. People with C6 or C7 SCI typically have mean maximum voluntary contractions (MVCs) with the wrist extensors of around 0.46, 0.71, and 1.92 Nm, which correspond to manual muscle test grades of 3, 3+, and 4 [9]. Subjects in our study reported similar wrist extensor grades. For the range of grasp apertures depicted in Fig. 3, people with MVCs corresponding to these muscle grades would ideally be able to generate grasp forces between 3.8-5.1, 5.9-7.9, or 15.8-21.3 N with the MWDO. At grasp apertures similar to the width of a pinch force sensor (10-20 mm), we would expect users with these functional levels to generate approximately 8.5 N on average with the MWDO. Similarly, subjects in [9] generated grasp forces of 7.26 $\pm$ 3.48 N when wearing a commercially-available, body-powered wrist-driven device and subjects in [27] generated forces between 7.61-8.27 N when wearing a 3D-printed WDO design. Measurements in [34] and [35] indicate that a large number of ADLs can be performed with less than 10 N of grip force. At these force levels, the motor, accounting for the 3:1 bevel gear ratio, should provide at least 0.3 Nm; the motor in the MWDO (Pololu #3492 with 156:1 metal gearbox) provides up to 0.92 Nm.

III. Methods

In this work, we conducted the first formal study comparing passive and motor-assisted control performance of the MWDO [28] on people who have SCI. Using similar methods to those evaluated in our previous work [29], we assessed upper body motions during seated grasp and release tasks. First-hand user perspectives are critical to the iterative design process, yet infrequently utilized in most works on robotic wearable devices. Therefore, we conducted interviews with subjects to understand their perceptions of wearable assistive technology and their experience with our current device. Furthermore, we quantified the amount of time it took participants to complete the tasks and how frequently participants failed to complete tasks using the two control modes. We additionally introduced a new metric for assessing the overall upper body posture.

The human subjects test protocol used in this work was approved by the University of California, Berkeley Institutional Review Board #2020-02-12983.

A. Participants

Since injury at C5 is the second most common cervical SCI [36] and injuries often occur between neighboring cord segments, we recruited participants with SCI between C5-7 (for simplicity, denoted as SCI for the remainder of this work) and demonstrated wrist extension ability against gravity, without the support of a device. As listed in Table I, six eligible individuals participated in the study and wore the MWDO, weighing 330 g, on their right hand. Not all subjects completed the entire experiment, as noted in the last row of Table I. Even when the device was motorized, Subject 2 could not perform device-supported tenodesis grasp in hand postures where wrist extension opposed gravity due to device resistance, which prevented them from performing 2/3 of the experimental tasks. Subject 3 experienced poor alignment between their wrist and the device due to significant anatomical radial deviation; this caused enough discomfort that they requested to discontinue the experiment after completing 1/3 of the tasks.

Despite self-reports of the same neurological injury levels, as well as similar American Spinal Injury Association Impairment Scale (AIS) scores and wrist strengths, the six subjects exhibited highly varied manual function. At rest, Subject 1 and 3's hands naturally sat in a closed-fist posture and their finger tendons remained quite stiff. As a result, wrist flexion with gravity resulted in only a slight relaxation of their finger tendons, with no discernible grasp aperture. In contrast, Subject 2 had relaxed finger tendons, but this prevented them from generating unassisted tenodesis grasp strength (without a device) needed for tasks like holding and using a pen. Subjects 4, 5, and 6 could perform tenodesis grasp in their daily lives, though Subject 4 reported weakness in their tenodesis grasp strength. Due to the limited number of participants and this observed functional variation, we treated each subject as an individual case study for our analysis.

B. Experimental Procedure

We utilized the two MWDO control modes described in Section II-B, where grasping a 14 mm object required all subjects to reach α = 40 deg in *passive* mode and α = 25 deg in *motorized* mode. The starting control mode for each subject was randomized and we additionally alternated the control modes between trials to reduce learning effects. Since many subjects could not perform unimanual grasping without an assistive device, subjects donned the MWDO for all functional experimental tasks. Participants wore the same device during tasks in each control mode to constrain the study's focus to the impacts of shared actuation alone, while keeping added mass constant. Unstructured practice and rest time was allotted at the beginning of each trial, until participants reported feeling comfortable with the device operation.

Subjects sat in their personal wheelchairs at an adjustable-height table positioned to a height of their preference at the beginning of the experiment. Each subject self-selected a distance between 3.5 to 6.5 cm measured between the top of the their legs and the underside of the tabletop to provide adequate leg clearance. The resulting tabletop workspace sat approximately at elbow height.

Throughout the study, the Impulse X2E Motion Capture system (PhaseSpace, San Leandro, California, USA) recorded movement of the upper body via active LED markers at a rate of 120 Hz, and a Hero9 Black camera (GoPro, Inc., San Mateo, California, USA) recorded video of the frontal plane. Subjects donned the MWDO and active LED markers on their

TABLE I
PARTICIPANT DEMOGRAPHICS

	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6
Sex	Female	Female	Female	Male	Male	Male
Age	64	42	62	35	33	35
Injury Level	C5-6	C5-6	C5-6	C5-6	C5-6	C5-6
Years Post-Injury	50+	18	45+	16	12	19
AIS Score	A	A	A	A	A	B
Study Completion	100%	33%	33%	100%	100%	100%

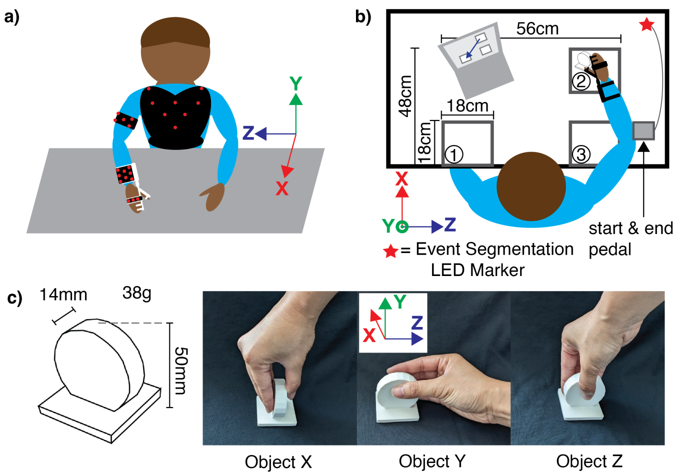

Fig. 4. Experimental setup: a) LED markers positioned on subject's upper body. b) Schematic of experimental workspace including marked (1) contralateral, (2) distal, and (3) proximal locations with respect to subject's right arm. c) Experimental test object and three orientation constraint configurations for grasp and release tasks, from the perspective of the participant. Naming convention corresponds to the world frame axis around which the hand closes.

torso, upper arm, lower arm, and hand with the assistance of a researcher (Fig. 4a). At the beginning of the experiment, we recorded calibration postures to identify the shoulder joint location during analysis, since markers could not be securely affixed to the shoulder region over clothing.

Each trial began with the subject sitting upright with their arms at their sides, approximately 90 degrees of elbow flexion, and palms facing inward. The subject would then rest their hand on the pedal to the right of their workspace to initiate the start of a task (Fig. 4b). Within each trial, the subject performed a set of grasp and release tasks. Each task consisted of the subject removing their hand from the pedal, grasping an object in a designated start location, transporting the object to a designated end location, releasing the object, and returning to the pedal to indicate the end of the task. A screen visually presented the instructions for each task throughout each trial for the subject to follow along. Three locations were selected to represent one region within and two regions beyond the ideal ergonomic reach envelope [37]. We denote these locations as (1) contralateral, (2) distal, and (3) proximal regions of the workspace with respect to the device-donned limb, as referenced in Fig. 4b. Each trial contained the same order and pattern of grasp and release tasks, where subjects moved the object clockwise then counter-clockwise through the target locations, starting at the contralateral location.

We 3D-printed a lightweight version of the paperweight object from the original Grasp and Release Test object set [38], and instructed participants to grasp and release it throughout each trial in one of three orientations: constraining the hand to close around the X axis, the Y axis, or the Z axis of the world frame defined in Fig. 4c. For the remainder this work, we refer to these orientation constraints as Object X, Object Y, and Object Z, respectively. If the subject dropped the object, failed to grasp it on the first attempt, or failed to release it on the first attempt, the researcher recorded the event and reset the object for the subject to repeat the task until they were successful. These instances were otherwise omitted from analysis; only successful trial movements and durations were considered. Subjects completed four replicates of each trial using each control mode with one object orientation constraint before continuing to the next orientation constraint. The first replicate was treated as a formal practice trial and excluded in the final analysis. The order of the orientation constraints was randomized for each participant. We analyzed 108 total trials for each of the subjects who completed the entirety of the study (1, 4, 5, and 6), and 36 total trials for each of the subjects who completed a subset (2 and 3).

Subjects were additionally surveyed throughout the experiment on their perception of difficulty for each object constraint, and each combination of mode, object constraint, and workspace location. Following the physical portion of the experiment, we removed the wearable materials and interviewed each subject on a variety of topics to identify their needs and perceptions surrounding wearable assistive technology and the MWDO device modes they experienced.

C. *Quantitative Metrics*

Prior to performing data analysis, we isolated the data for each task within the trial, defined as a single replicate of the grasp and release event from one location to another location for a single mode and a single object constraint. Within each task, we further segmented the data into the five phases of grasp and release: reach, grasp, transport, release, and return. Unlike those with normative hand function, people with C6 SCI exhibit the phases of reach-to-grasp sequentially [39]. Thus, we segmented these phases using a velocity threshold method. We first applied a 3rd-order Savitsky-Golay filter with a frame length of 141 to the positional data of the hand and calculated the hand velocity using the Cartesian distance traveled between data frames. Next, we identified a velocity threshold band for each subject based on their typical hand velocities and split the task into the respective phases based on when the velocity profile crossed through the band. Finally, for tasks with atypical variations in velocity, we compared

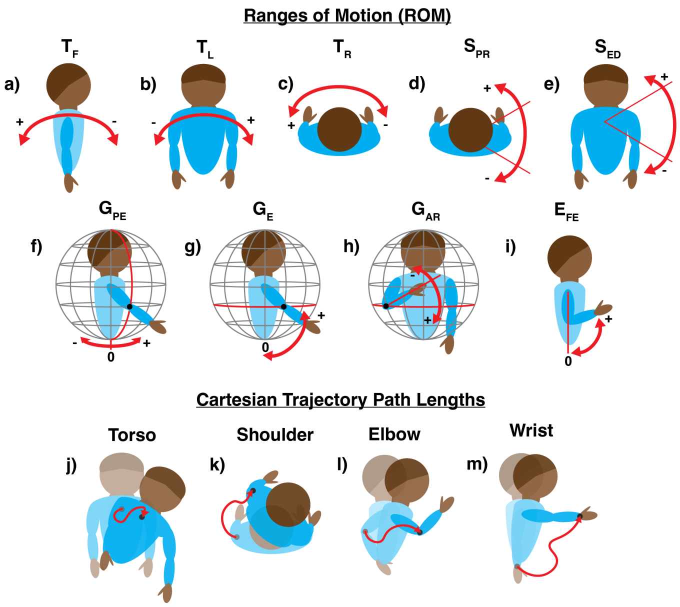

Fig. 5. Measured kinematic metrics for upper body compensation including a-i) the range of motion of body angles (defined in text) and j-m) the Cartesian path length of body points. Adapted from [29].

video data with the task motion capture data to determine the appropriate segmentation times manually.

We measured the performance of the two MWDO control modes through the following metrics:

1) **Task Failures**: the number of unsuccessful events described in Sec. III-B, along with the phase in which the failure occurs.
2) **Movement Time**: the time spent in each phase and over the full grasp and release cycle.
3) **Body Angles**: the range of motion (ROM) of the trunk and joints pictured in Fig. 5a-i throughout the overall grasp and release cycle.
4) **Path Lengths**: the Cartesian distance traveled by the body points pictured in Fig. 5j-m throughout the overall grasp and release cycle.
5) **Rapid Upper Limb Assessment (RULA) Scores:** ergonomic risk assessment score of static overall posture at each time point [40].

For analyses of metrics 2)-4), the mean of the three replicates was used to represent subjects' performance across multiple iterations of a single task.

D. Kinematic Assessments

To measure body compensation using metrics 3)-5), we first modeled the upper body as five distinct rigid bodies: the thorax, shoulder girdle, arm, forearm, and hand. Body angles (Fig. 5a-i) were calculated according to the International Society of Biomechanics recommendations for local coordinate systems and order of motion rotations [41]. These angles included extension/flexion (T_F), lateral rotation (T_L), and axial rotation (T_R) of the thorax, protraction/retraction (S_{PR}) and elevation/depression (S_{ED}) of the sternoclavicular joint, the plane of elevation (G_{PE}), elevation (G_E), and axial rotation (G_{AR}) of the glenohumeral joint, and flexion/extension (E_{FE}) of the elbow joint. Joint centers were approximated mathematically using marker positions and the anatomical measurements taken of each subject. We generalized the clavicle and scapula to the movement of an overall shoulder girdle due to lack of discrete markers around the shoulder region. ROM of the body angles was calculated as the difference between the maximum angle and the minimum angle reached over the course of a task. We calculated the total Euclidean distance traveled of the suprasternal notch (torso), glenohumeral joint (shoulder), elbow joint, and wrist joint (Fig. 5j-m).

Injury and musculoskeletal disorders can often be attributed to awkward postures and while metrics like ROM can assess the posture of individual joints, there is no objectively quantifiable method of assessing the overall body posture in individuals with functional impairments, such as SCI. Ergonomists use the Rapid Upper Limb Assessment (RULA) as a tool to quickly identify body postures that may lead to heightened risk of upper extremity disorders in the workplace. The RULA assigns scores to each region of the upper body based on local postural angles [40]. The output of this assessment is a score on a scale of 1 to 7, with score ranges corresponding to Action Levels (ranging from 2, least concerning, to 4, most concerning) that suggest how urgently a given posture needs to be adjusted. A few recent assessments of assistive technology [42], [43] have begun to use the RULA, and we apply it here as a global measure of problematic body posture with the understanding that the tool may not be optimized for people with tetraplegia.

E. Interview Analysis

Prior to the study, we developed an interview guide including topics such as perception and effects of the MWDO, ideal device characteristics, typical activities, common tools used, and the use of tenodesis grasp in everyday life. We conducted a semi-structured interview with each subject directly following the device-worn tasks and recorded this data with the same video equipment as above. Audio from the recordings was extracted and transcribed, then compiled and organized into an affinity diagram to perform hierarchical analysis.

IV. Results

Subjects reported their rankings of object difficulty between 1 (easiest) and 3 (hardest), their perceived most difficult locations to manipulate each object, and their preferred control mode, shown in Table II. Notably, all subjects preferred motorized control to passive control. Other metrics, however, showed variation between modes.

A. Task Failures

Failures during the grasp and release cycle occurred more frequently when subjects operated the MWDO in the passive control mode, compared to the motorized control mode, as depicted in Fig. 6 for the grasp and release phases. Only four failures occurred across the subject pool during the transport phase, omitted from Fig. 6, three of which occurred with

TABLE II
SUBJECT-REPORTED FACTOR DIFFICULTY

	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6
Object X Rank	3	-	-	3	3	3
Object Y Rank	2	1	-	1	2	2
Object Z Rank	1	-	1	2	1	1
Object X Location	Contralateral	-	-	Distal	Distal	Distal
Object Y Location	Contralateral	Distal	-	Contralateral	Contralateral	Distal/Contralateral
Object Z Location	Contralateral	-	Proximal/Contralateral	Contralateral	Contralateral	Contralateral
Mode Preference	Motorized	Motorized	Motorized	Motorized	Motorized	Motorized

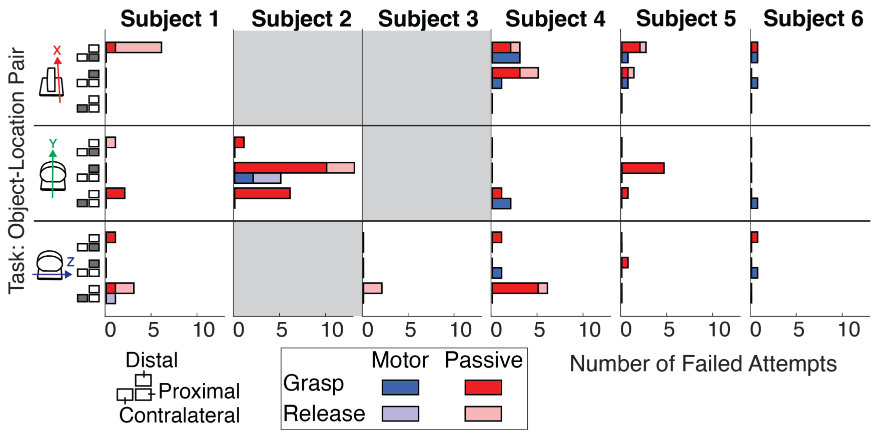

Fig. 6. Failures during grasp and release in each control mode. Failures include object drops and instances where the object was not grasped or released successfully on the first attempt.

passive control and one of which occurred with motorized control. Subjects 2, 4, 5, and 6 exhibited more failures during the grasp phase than the release phase, while Subject 3 exhibited the opposite and Subject 1 exhibited a less clear overall trend between phases.

Subject 1 experienced most failures when operating the MWDO in the passive mode, and only one task failure when utilizing the motorized mode. Subject 1 reported this task (Object Z in contralateral location) to be one of the most challenging and recorded failures of this task in both device modes. Subject 2 also experienced more failures in passive mode and the highest number of failures occurred with Object Y in the distal location. They similarly reported this location to be the most difficult, however, the motorized control mode reduced over half the number of failures experienced in the passive control mode. Subject 3 experienced few failures; those they experienced occurred with passive mode at the contralateral location, where they reported difficulty in releasing the object.

Subject 4 experienced more failures overall with the passive mode than motorized mode, but with less distinct patterns within tasks. Motorized assistance reduced the number of failures for two of the tasks they reported most challenging (Object X in distal location and Object Z in contralateral location), but increased the number of failures for the third reported challenging task (Object Y in contralateral location). Subject 5 also experienced more failures in passive mode, with motorized assistance reducing failures in two of their reported most challenging tasks (Object X in distal location and Object Y in contralateral location). In contrast, Subject 6 experienced more failures with the motorized mode, but never experienced more than one failure per task in each mode.

In most participants, the addition of motorized assistance helped reduce the number of grasp and release failures, especially during the tasks where they noted particular difficulty. Failed trials were omitted from the analysis of subsequent metrics.

B. Movement Time

For the set of grasp and release tasks completed by each subject, Subjects 1, 2, and 4 reduced their overall trial completion time when using motorized control (Table III). Additionally, they completed at least 66.67% of their tasks faster with motorized control than with passive control, although Subjects 2 and 4 showed larger time differences between tasks in the two modes (Fig. 7). Subjects 3 and 6 finished around 50% of their tasks faster on average with motorized control than with passive control, completing the full set of tasks within a 2 second difference between the two control modes. As shown in Fig. 7, these two subjects commonly exhibited task-level time differences of around 1 second or less between the two modes. Alternatively, the total time for Subject 5 to complete the full set of tasks was faster in the passive mode and they completed only 38.89% of individual tasks faster with the motorized control, though their task-level differences were also commonly around 1 second or less. Subjects 2 and 3, who completed only a subset of the experimental tasks, did not exhibit distinct trends from the subjects who completed the full set of experimental tasks.

Fig. 8 shows the breakdown of the time that subjects spent in each of the grasp and release phases. Compared to Subjects 1,

TABLE III
TOTAL TIME SPENT BY EACH SUBJECT

Time (s)	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6
Total Passive	379.09	169.48	96.21	400.68	244.21	221.13
Total Motor	361.84	142.00	97.00	362.03	256.24	222.27
Difference	17.25	27.48	-0.79	38.65	-12.03	-1.14

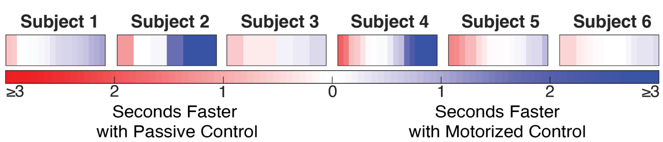

Fig. 7. Difference in completion time for the tasks completed by each subject. Reds indicate that passive mode resulted in faster task completion than motorized mode and blues indicate that motorized mode resulted in faster task completion than passive mode. Darker shades indicate larger differences in time between the two modes. Each task consists of moving one object between a pair of locations.

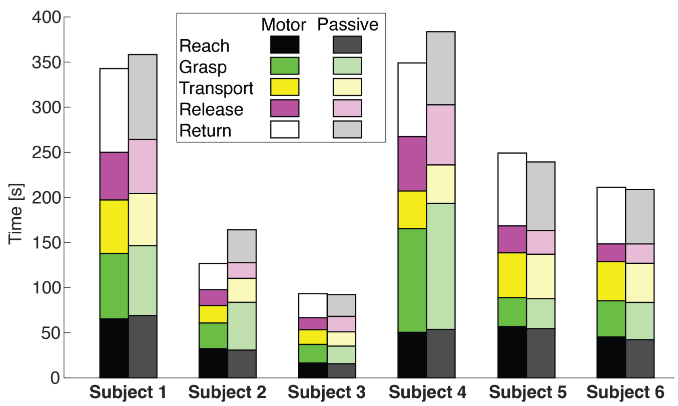

Fig. 8. Time spent in each phase of the grasp and release cycle. Colored regions indicate phases where the hand and object are in contact.

4, 5, and 6, the reduction in total time spent by Subjects 2 and 3 reflect the smaller number of tasks they performed. When operating the MWDO with passive control, Subjects 2 and 4 spent more time in the grasp phase compared to the time they spent in the transport or release phases. Adding motorized assistance, however, reduced the amount of time these two subjects spent grasping. Subjects 1 and 3 spent a similar amount of time in each object contact phase and Subject 5 spent most time contacting the object in the transport phase. Subject 6 spent a similar amount of time contacting the object in the grasp and transport phases.

Overall, some participants completed tasks faster when operating the MWDO in the motorized control mode than the passive mode. For those who did not, the differences in task completion time between the two modes were small. An extended table including each subject's movement time for each task can be found in the Supplementary Material (S1).

C. Body Angles

For the set of tasks performed by each subject, motion capture showed that operating the MWDO with the motorized control mode altered the ROM of a number of body angles compared to operation in the passive mode. Examples of these altered postures are shown in Fig. 9.

Motorized control reduced all three thorax motions in at least 50% of tasks for Subjects 1, 2, 3, and 4, with the largest differences in ROM occurring in Subject 1 (reduced T_L in 61.11% of tasks and reduced T_R in 83.33% of tasks) and Subject 3 (reduced T_F in 83.33% of tasks, reduced T_L in 100% of tasks, and reduced T_R in 83.33% of tasks), shown in Fig. 10a. At the shoulder girdle, motorized control resulted in reduced protraction/retraction (S_{PR}) in 100% of tasks for Subject 2 and few prominent differences in the other five subjects. At the glenohumeral joint, differences in ROM varied greatly between subjects. Subjects 1 and 4 showed tendencies toward smaller glenohumeral ROMs with motorized control, while Subjects 3 and 5 showed tendencies toward smaller glenohumeral ROMs with passive control. Subjects 2 and 6 did not show a prominent difference between the two modes at this joint. Motor assistance reduced elbow flexion and extension (E_{FE}) for at least 50% of tasks in every subject.

Each subject showed a unique kinematic response to the motorized control mode, compared to the passive control mode. An extended table including each subject's ROM for each task can be found in the Supplementary Material (S2).

D. Path Lengths

As seen in Fig. 10b, Subjects 1, 2, 3, and 4 reduced the travel distance of all their body points in at least 66.67% of the tasks they completed. When summing the total distance traveled across tasks in each mode, the same subjects exhibited shorter travel distances of all their body points when using motorized control than passive control, shown in Table IV. Conversely, Subjects 5 and 6 exhibited shorter total travel distances for most body points when using passive control than motorized control, with the exception of Subject 5's wrist. Subject 5 further showed reduced wrist travel distance in 61.11% of tasks, but reduced elbow travel distance in less than 33.33% of tasks with the addition of the motor. Subject 6 exhibited reduced travel distance in all body points more frequently with passive control than motorized control.

Compared to the rest of their body points, the movements of Subjects 1, 2, and 5 resulted in the greatest difference in travel by the elbow, while the movements of Subjects 4 and 6 resulted in the greatest difference in travel by the wrist. Subject 3 showed similar differences across the torso, shoulder, and elbow. In Subjects 1, 2, 4, and 5, body segments closer to the experimental object showed larger differences in distance traveled between the two control modes, while the patterns of motion in Subject 3 showed the opposite and Subject 6 showed no distinct trend. An extended table including each

Fig. 9. Comparison of sample postures from each subject between the two device modes.

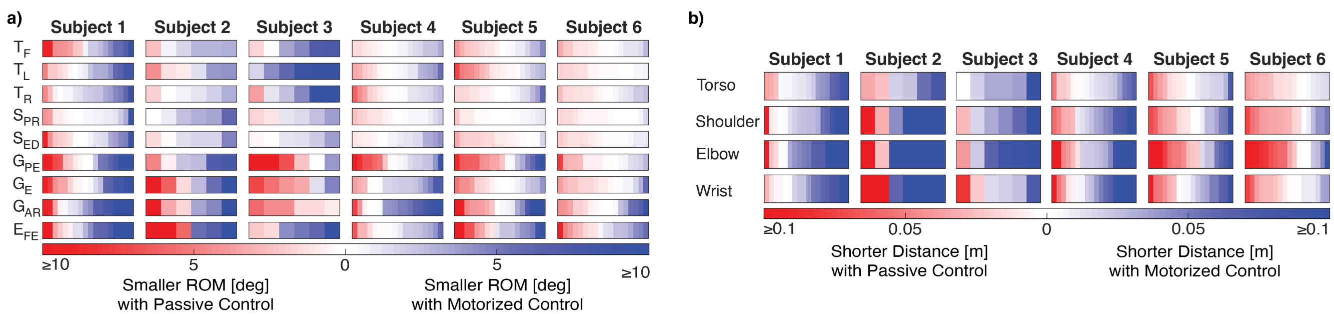

Fig. 10. Difference in compensation via a) ROM, and b) Cartesian distance traveled, for the tasks completed by each subject. Reds indicate that passive mode resulted in less compensation than motorized mode and blues indicate that motorized mode resulted in less compensation than passive mode. Darker shades indicate larger differences in compensation between the two modes. Each task consists of moving one object between a pair of locations.

TABLE IV
TOTAL DISTANCE TRAVELED BY SUBJECTS' BODY POINTS

Point	Distance (m)	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6
Torso	Passive	30.44	7.77	4.67	11.68	11.57	8.88
	Motor	29.24	7.42	3.66	11.06	11.66	9.47
	Difference	1.20	0.35	1.01	0.62	-0.09	-0.59
Shoulder	Passive	46.24	15.20	7.57	26.83	23.49	17.32
	Motor	44.36	13.67	6.57	25.36	23.56	18.16
	Difference	1.88	1.53	1.00	1.47	-0.07	-0.84
Elbow	Passive	79.93	28.05	15.57	57.43	55.49	40.43
	Motor	76.46	24.45	14.55	55.34	56.41	42.08
	Difference	3.47	3.60	1.02	2.09	-0.92	-1.65
Wrist	Passive	73.71	30.91	20.24	63.61	67.97	49.53
	Motor	71.36	27.83	20.15	61.21	67.54	50.13
	Difference	2.35	3.08	0.09	2.40	0.43	-0.60

subject's Cartesian path length for each task can be found in the Supplementary Material (S3).

E. RULA Scores

Time spent in each RULA score range is shown in Fig. 11. Similar to Fig. 8, the reduction in percent time spent during the full experiment by Subjects 2 and 3 reflect the subset of the experiment that they performed. When using the MWDO with motorized control as compared to passive control, all subjects except Subject 6 spent more time in less concerning postures (Action Level 2) and less time in more concerning postures (Action Level 3). At Action Level 4, where the RULA dictates that immediate change to the posture is needed, trends across participants varied. Subjects 1 and 5 spent more time in these postures when using motorized control than passive control, Subject 2 spent approximately equal time in each control mode, and Subjects 3, 4, and 6 spent more time in these postures when using passive control than motorized control.

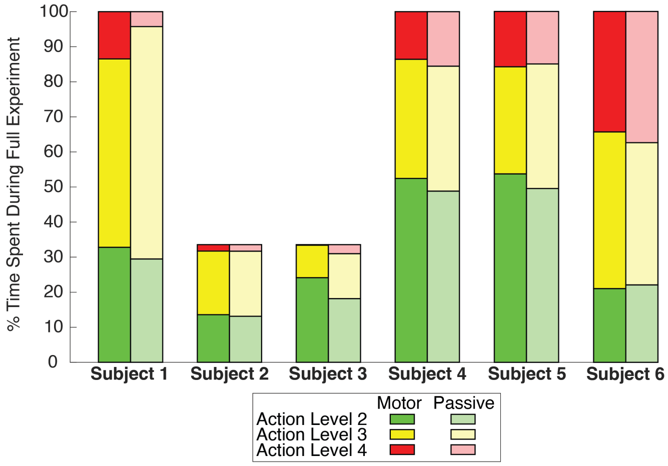

Fig. 11. Percent time spent in each RULA Score range throughout full experiment. Larger Action Level values correspond to increased postural risk.

F. Common Interview Themes

In the interviews, feedback was overall positive about the device actuation method, but subjects noted some concerns. It is important to acknowledge that responses in the context of research studies can be affected by courtesy bias or demand characteristics, where participants unintentionally adapt their responses toward what they think the researcher wants to hear.

All subjects reported a preference for motorized control over passive control and their reasoning centered around the feelings of greater grasp security. In particular, Subject 1 commented that with motor assistance, "I trusted that [the device] was going to hold [the object]." Subjects 1, 3, and 6 also commented directly on the stronger grip they felt the motor assistance provided. This user sentiment of increased strength is particularly interesting since the motor in the MWDO does not directly enhance the grasping forces applied to the object. Four subjects additionally alluded to enhanced ease of use during operation with the motorized control. Examples of this included that the motor assistance made it "easier to let go of things" and that "when I did not have the motor, I had to try harder to keep [the object] in the grip."

Despite these positive sentiments, Subjects 1 and 4 commented that they would prefer to use an MWDO-like device for specific tasks only, not wear continuously throughout the day. One concern was the bulkiness and weight of the device, which are increased by the presence of the motor. All subjects additionally clarified that in order for them to adopt a new device, it would need to be easy to use, don, and doff, which they noted they would be unable to do with the MWDO independently. Subject 5, the only subject in the study who used a manual wheelchair, further noted that any prospective device that limited their ability to push their wheelchair (such as the MWDO) would be a "deal-breaker."

V. Discussion

A. Observations of Subject Variability

Supplementing the MWDO's primary body-power with motor assistance to change the wrist-hand kinematic relationship resulted in mixed outcomes for the six individuals in this study. While all subjects preferred using the MWDO in the motorized mode and it often helped reduce failures, task completion time and measures of body compensation appeared to vary across subjects. This is anticipated given the wide set of morphologies, abilities, and approaches of each subject, and since we did not impose additional constraints on body postures to allow subjects to use the device realistically.

Subjects showed notable variability in their trunk motion, which is consistent with frequent findings of distinct trunk movement strategies exhibited by people with SCI, like leaning and bracing with the arm for balance [44], [45]. We observed Subject 1 brace their left arm on the armrest of their wheelchair during many tasks performed while wearing the MWDO in passive mode, but less often with the addition of motorized assistance. Subjects 5 and 6, on the other hand, hooked their left arms around the push handles of their wheelchairs bracing their trunk against their chair's backrest for tasks in both modes. Prior works have shown that active robotic assistive devices can reduce ROM in proximal regions of the body compared to passive body-powered devices [46], [47]. The measured trunk kinematics of the subjects in this study suggest that combining aspects of both active and passive device control can help reduce trunk compensation in the best cases (like for Subjects 1, 2, and 3), or have minimal effect on trunk movement in the worst cases (like for Subjects 4, 5, and 6).

Additionally, we observed shoulder complex instability in Subject 2, which is consistent with the large number of muscles around the glenohumeral joint that retain only partial innervation at the C5-6 injury levels [5]. In Subject 3, we observed radial deviation in the wrist, which is common in people with cervical SCI due to paralysis of the ulnar deviators [48]. The design of future wearable devices should therefore be customizable to fit a wider variety of body morphologies.

B. Test Methodology and Usability

With the adoption gap in mind, we designed this study to assess the key factors that contribute to good usability of a system: effectiveness, efficiency, and satisfaction [49]–[51]. The decrease in task failures with motor assistance suggests device *effectiveness* at improving dexterity and participants favored this reduced operational error. For example, Subject 3 emphasized that "dropping things is a continual [frustration]." Survey data similarly indicates that poor device performance highly correlates to assistive device abandonment [23], thus, improved device efficacy with shared actuation could contribute to greater device acceptance and retention.

Additionally, task performance speed and perceived effort relate to task *efficiency* [52], which many prioritized. Subject 2 explained that they aim to do most grasping activities as fast as possible because "there's probably less chance of me dropping it." Using the MWDO's motorized assistance, half of the subjects reduced their task completion time, and the other half showed similar speeds between the modes. Subject 2 also commented that "when the motor was on...I have to exert maybe 50% of the effort and thought." Body powered devices that provide extended physiological proprioception (EPP) can contribute to such efficiency. Our work shows that the addition of a motor in parallel with body power can improve efficiency without impeding EPP.

Finally, conducting post-study interviews enabled evaluation of device *satisfaction*. Regarding the experimental human-robot shared actuation system alone, participants commonly reported motor-related trust and unanimously preferred the motorized mode. Despite infrequent improvements in upper body kinematics, Subject 5 expressed delight with the motorized control, declaring, “It’s fun. It’s like being Iron Man!”

C. Impact of Motorized Control

Our shared system, which combines body-power and robotic assistance, created a productive compromise for the tradeoff between passive and active devices in Subjects 1, 2, 3, and 4. These subjects both reduced unnecessary body movements that often afflict passive control, and also completed tasks faster and with fewer errors, a frequent challenge of purely active device control. The tradeoff between these benefits and drawbacks of passive and active assistive technology could be one reason that neither is predominantly preferred by users over the other [12], [13], [47], [53], but combining the two together could be more desirable.

In contrast, Subjects 5 and 6 showed typically smaller magnitudes of overall body compensation, with the exception of compensation related to glenohumeral joint movement. Compared to the other subjects, the motorized control in fact increased this compensation frequently in these two subjects. Compensatory motion has been correlated to device abandonment [54] and such movements can increase load and intramuscular pressure on regions like the shoulder [55], where pain and overuse injuries commonly afflict people with SCI [56], [57]. For these individuals, iteration of the current state of the shared system is necessary to determine its potential benefit. An ideal system would harness the benefits of both passive and active technology and decrease the tendency toward awkward postures, a significant risk factor for musculoskeletal disorders [58].

Though we observed varied kinematic responses, the narrative data implied that subjects regularly experienced perceptions of embodiment when utilizing the shared system and favored it to solely passive actuation. The system felt intuitive to operate, especially with motorized assistance, and they additionally appreciated the ability to use their own body for single-handed grasping with the MWDO, which was the first time for many. Active actuation can traditionally diminish sense of embodiment by reducing EPP [14], but the results of this work indicate that the motor does not impede this user experience, and can even enhance performance for some.

D. Limitations and Future Work

The limited number of participants in this study make it difficult to generalize our findings to the broader population of people with SCI. Indeed, we observed a wide range of abilities and experiences within the six people who participated in this study. It is common for target populations of accessibility research, such as people with motor disabilities, to often exhibit more variance in abilities and experience than normative populations [59], [60]. For this reason, such broad conclusions should be drawn with caution. In fact, dissimilarities between users and barriers to use, like those we observed in Subjects 2 and 3, highlight the need for a user-centered approach to assistive technology development that supports personalization [61], [62]. For example, new design changes should address these observed barriers to increase the accessibility of wrist-driven devices within this population. Future works should also include measurements such as baseline ROM as well as muscle strength and tone to provide additional context for the outcomes of individual participants. Including the end users of assistive devices and more detail of their personal characteristics in the process can facilitate the transition of the technology from research labs to the real world [63].

The MWDO is heavier than a standard WDO due to the weight of the motor and transmission. In this study, we hold weight constant across all tests. We therefore do not measure baseline performance without the presence of the motor. Future work should measure the negative effect that this weight has on, for example, fatigue. Regardless, this study shows that the control method of assistive devices is one aspect that would benefit from personalized design. Towards this end, the MWDO testbed can be modified to explore new strategies that share control between the robot and the individual human needs and preferences. One potential exploration could focus on design iterations that harness larger mechanical advantage for wrist-driven systems. While body-power alone limits MA for practical use, actuation of higher MA mechanisms can be achievable with the use of shared body- and motor-powered control. While we expect that combining these control aspects holds benefits for adoption over active options due to the preserved sense of EPP [15] and natural user intent recognition, future work should additionally test these hypotheses.

Finally, in this evaluation of MWDO control methods, we applied the RULA, a measure originally intended for risk evaluation of workplace upper limb disorders [40]. This assessment of upper body biomechanics has yet to be validated for the evaluation of people with impacted motor function. We believe introducing global measures of body posture to the assessment of assistive technology can improve usability and safety by reducing awkward postures known to contribute to risk of musculoskeletal disorders [58]. Such new metrics should be established for this purpose in the future.

VI. Conclusion

We assessed a new system that couples wrist-driven actuation with motorized assistance in a wearable exoskeletal device, intended to assist with grasping in people with SCI. The results of this study highlight the experiences of six individuals with C5-6 SCI and discuss the impacts of combining body- and motor-powered assisted grasping (*motorized* control), compared to body-powered grasping alone (*passive* control) in wrist-driven devices. Rapid technological growth and engineering advancements in the field of wearable assistive devices have yet to translate to widely accepted solutions for people with C5-6 SCI. This usability study on the shared actuation of the MWDO between the user and the motor presents an initial step toward bridging the gap between research and the real world. Specifically, it shows that using a motor to modulate grasping kinematics, rather than directly enhancing grip strength, is an unconventional approach with potential to improve grasping and device embodiment.

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