Hand Extension Robot Orthosis (HERO) Glove: Development and Testing With Stroke Survivors With Severe Hand Impairment

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Abstract—The hand extension robot orthosis (HERO) glove was iteratively designed with occupational therapists and stroke survivors to enable stroke survivors with severe hand impairment to grasp and stabilize everyday objects, while being portable, lightweight, and easy to set up and use. The robot consists of a batting glove with artificial tendons embedded into the glove's fingers. The tendons are pulled and pushed by a linear actuator to extend and flex the fingers. The robot's finger extension and grasp assistance are automated using inertial measurement unit signal thresholds. Five stroke survivors (Chedoke McMaster Stroke Assessment – Stage of Hand 1-3) put on the HERO Glove in 1-3 minutes, with assistance. The stroke survivors performed significantly better on the Box and Block Test (2.8 more blocks transferred, $p < 0.01$) while wearing the HERO Glove than when not wearing the glove. Four stroke survivors could only transfer blocks while wearing the HERO Glove. The HERO Glove enabled these stroke survivors to more fully extend their index finger (an increase of 97.5°, $p < 0.01$) and three of five stroke survivors were better able grasp a water bottle. Therapists and stroke survivors suggested increasing the HERO Glove's grip force assistance and valued the glove's portability, lightweight design and potential usefulness in assisting with task-based therapy.

Index Terms—Rehabilitation robotics, assistive technology, occupational medicine, hand therapy, stroke, wearables.

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I. INTRODUCTION

FIFTEEN million individuals worldwide experience a stroke each year with 50,000 of these cases occurring in Canada [1]. Approximately two-thirds of these individuals will experience neurological deficit [2] and half will never fully recover the hand function required to perform activities of daily living independently [3]. High-intensity, personalized therapy is needed for stroke survivors to regain their hand range of motion (ROM), strength and coordination, and translate recovery gains into daily task independence [4], [5]. The coaching and motion assistance required is time and resource intensive, making it difficult for therapy clinics to supply at the appropriate intensity [6], [7]. After their therapy programs are complete many stroke survivors still struggle to extend their fingers to prepare for a grasp and grip with enough strength to stabilize objects, thereby making the hand difficult to integrate into daily activities at home.

Therapists and stroke survivors have steered technology designers to create wearable robotic hand orthoses that can make hand therapy more engaging and reduce the activation barrier to performing unsupervised exercises at home [8]–[10]. Current devices have been developed for in clinic use and have shown recovery benefits close to minimum clinically meaningful differences (i.e. 1 to 6 points on the Fugl-Meyer Assessment-Upper Extremity (FMA-UE) and Motor Activity Log) [11]–[16]. By improving the portability, affordability and ease of use of wearable robotic hand orthoses, they could be more easily integrated into home therapy programs to monitor active movement, assist directly in daily activities and increase neuromuscular recovery [17]–[19].

A small number of wearable hand robots intended for home use have been evaluated with people with affected hands. These robots' assistive capacity has been shown to enhance hand function and performance on activities of daily living (ADLs). A summary of these and other recently-developed wearable hand robots, including their components and trial efficacy, is presented in Supplementary Table I. For stroke survivors with moderately-affected upper extremities, Peters *et al.* [20] showed that elbow, wrist, and finger assistance improved FMA-UE scores by 13% as well as cup and utensil grasping. For stroke survivors with severely-affected
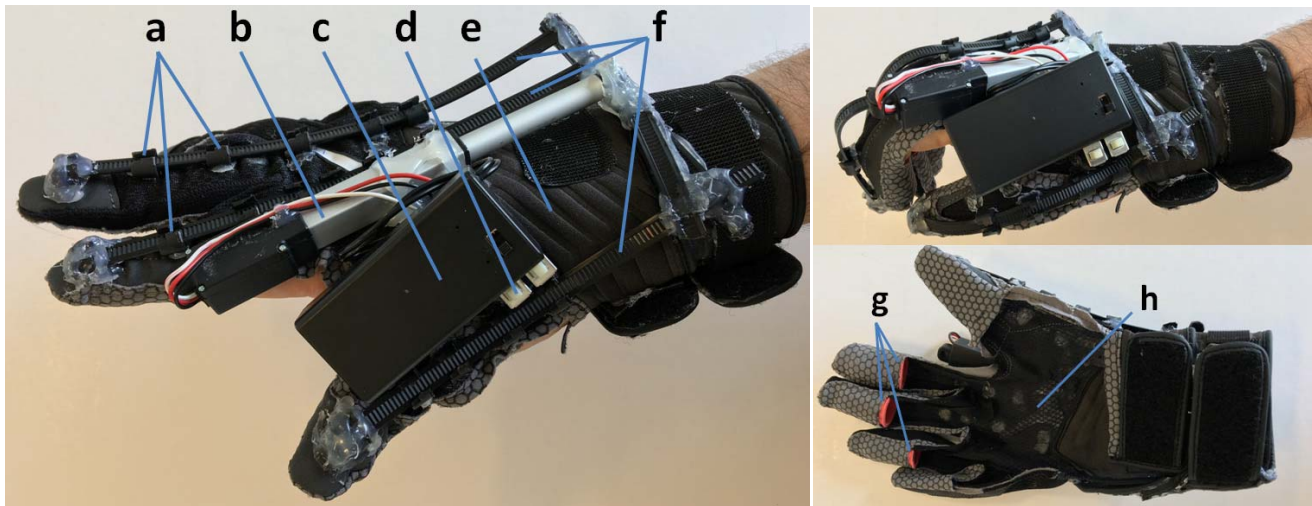
Fig. 1. The HERO Glove consists of (a) cable tie pawls, (b) a linear actuator, (c) a 9V battery pack, 9V battery and microcontroller with an inertial measurement unit, (d) buttons to control manual mode and select between the manual and automated modes, (e) a batting glove, (f) cable tie tendons, (g) finger thimbles, and (h) an open palm. The HERO Glove is shown extending (left) and flexing (top, right) the relaxed fingers and thumb.

hands, Park *et al.* [21] showed that a 40N extension force could extend low-tone but not high-tone fingers, making essential skills like cylindrical grasping difficult [8]. In addition, stroke survivors can have weakened grip strength and may need at least 15N of palmar or pinch grasp assistance to complete daily tasks, as demonstrated by Cappello *et al.* [22] for spinal cord injury survivors. As a result, multiple sizeable actuators and energy storage units have been integrated into these robots, which are not aesthetically pleasing and increase the weight such that an arm support is required [9] or require additional cabling and donning processes for back, belt or wheelchair mounting that may reduce usability [22]–[26]. Buttons, electromyography (EMG), electroencephalography (EEG), voice and vision have been used to sense the user's intent, in order to trigger assistance and motivate spontaneous use of the affected upper extremity. However, the accuracy in detecting the user's intent during robot-assisted trials has only been reported in Soekadar *et al.* (with a 16.3% false-positive rate) [25] and stroke survivors with severely impaired upper extremities are often excluded from studies because the sensing modality cannot accurately detect their intent [20].

This article details the design and evaluation process taken by our transdisciplinary team of researchers, therapists and stroke survivors at the Toronto Rehabilitation Institute - University Health Network (TRI-UHN) to develop the Hand Extension Robot Orthosis (HERO) Glove. This glove has been designed to reduce barriers to using the stroke hand in daily life by enabling stroke survivors with severe hand impairment to grasp and stabilize everyday objects through mechanical assistance of finger and thumb extension and flexion. Key attributes of the HERO Glove are its portability, light weight, ease of donning, use of affordable components and inertial measurement unit (IMU) triggered control method for one-handed use. The HERO Glove's motion assistance capabilities are validated with stroke survivors to understand its efficacy

in enhancing daily task independence and provide design guidance for wearable robotic hand orthosis designers.

II. METHODS

A. HERO Glove Design

The HERO Glove, shown in Fig. 1, was iteratively designed and tested with occupational therapists specialized in stroke therapy, engineering students and two chronic stroke survivors with severe hand impairment [Stage 3 and Stage 1 hands (out of 7) - Chedoke McMaster Stroke Assessment [27]; level 2 tone (out of 4) - Modified Modified Ashworth Scale [28]], both of whom presented with high finger and wrist tone and showed no active finger extension. Initial requirements for the wearable hand robot were generated through bi-weekly meetings between therapists and engineers and conversations and robot testing with the chronic stroke survivors. Previous interview findings were used to prompt these conversations [8], [9]. Quantitative specifications, shown in Table I, were assigned for each requirement after discussing the specifications of previous wearable hand robots.

The HERO Glove transmits extension and flexion forces to the index and middle finger and thumb through cable ties. The ends of the cable ties are fixed to the fingertips of a batting glove (Mizuno Supreme, Men's Large) and slide through cable guides fixed to the dorsal side of the glove. The cable ties are actuated by push-pull forces from a single linear screwdrive servo actuator (Actuonix, L12-R, 210:1, 80N max force, 50mm stroke length) that is mounted on the dorsal surface of the glove in-line with the two proximal sets of cable guides. When the actuator extends, the cable ties pull on the fingertips of the batting glove and apply a straightening force on the dorsal side of the fingers. When the actuator contracts, the cable ties apply a bending force to the fingers because the batting glove restrains their axial motion. The actuator is non-backdrivable, which conserves power when extension or grip

assistance is required for long periods of time. The actuator and the onboard microcontroller (tinyTILE Intel Curie) are powered by a 9 Volt battery (Energizer, Rechargeable NiMH). Separate HERO Gloves were created for the left and right hands to make the study more inclusive. The glove's fingertips have high-friction silicone webbing for added grip. Perforated rubber thimbles (Staples Fingertips) were glued inside the finger tips to increase comfort and make finger insertion easier while minimizing any additional loss of fingertip sensation. The HERO Glove's specifications are shown in Table I.

B. HERO Glove Control Strategy

The user operates the glove using the two control modes shown in Supplementary Figure 1 and available at github.com/drossos/HERO-robot. The user can press the physical button to extend and flex the fingers or have the microcontroller automatically trigger assistance when the gyroscope reading from the inertial measurement unit (IMU) reaches a threshold. The purpose of the IMU-triggered automated mode is to keep the unaffected hand free and to motivate arm and wrist use as the IMU is positioned distal to the wrist. To determine the threshold values for triggering motion assistance, four able-bodied participants (age 18-35; 3 female) simulated moving their arm slowly while wearing the HERO Glove to perform the Box and Block Test [29]. Their gyroscope data provided a higher signal to noise ratio than their accelerometer data and a threshold value of 0.23°/s was selected. The glove alternates between triggering flexion and extension assistance when the user moves their hand with an angular velocity above the threshold and then stops moving for 0.8 seconds. After the actuator is triggered to move, there is a two second delay before the actuator can trigger again so the user can adjust their hand orientation during the grasp. This control scheme allowed users to reach for a block, stop for the block to be grasped, lift the block over the barrier and then stop to drop the block. The four able-bodied participants transferred 7, 4, 5 and 7 blocks in one minute using the right-handed HERO Glove with their hand relaxed. The actuator was correctly triggered 46 times (23 flexion; 23 extension), never triggered when undesired (0% false positives) and triggered later than desired twice (4% false negatives). This control scheme also allowed users to reach for the water bottle, stop to grasp it, lift up and put down the water bottle and then stop to release the water bottle.

C. Design Decisions Motivated by Iterative Testing

The HERO Glove was developed after creating and testing the intermediate prototype, shown in Supplementary Figure 2. The researchers assisted the stroke survivors to don, operate, and doff the intermediate prototype. Testing the intermediate prototype identified motion assistance and usability issues that motivated three key design iterations. First, cable ties were added for extension assistance in place of fishing wire. This enhanced comfort and alignment by distributing the force applied to the dorsal side of the finger and resisting twisting and out-of-plane bending. Cable ties were only positioned on the index and middle finger and thumb in order to maximize force. Ring and little finger tendons can be attached to

TABLE I
THERAPIST AND STROKE SURVIVOR DESIGN SPECIFICATIONS AND THE HERO GLOVE'S CAPABILITIES

Design Specification	HERO Glove Capability
Apply at least 10N of extension to each finger and the thumb [21], to enable cylindrical grasping [8].	~, *Partially meets specification*: Applies 80N total extension force across the index and middle fingers and thumb
Apply at least 15N of grip force [22] and ideally 67N [37]	**X**, *Does not meet specification*: Applies flexion motion assistance to the index and middle fingers and thumb, but negligible grip and pinch force
Untethered, weighs less than 400g, and profile less than 5cm to avoid obstructing ADL performance [8], [26]	✔, *Meets specification*: Wireless, weighs 192g (0.42lb) in fully-operable state (with all components in Fig. 1 included), maximum profile protrusion is 3cm above the wrist, which is when the actuator is extended.
Controlled by the affected hand with less than a 16% false positive rate [25]	~, *Partially meets specification*: Controlled by the affected hand with a 0-4% false negative and false positive rate during the BBT. Did not generalize well to some water bottle task components.
Does not hyperextend affected finger joints and pressure points eliminated [8]	**X**, *Does not meet specification*: DIP joint extended past 0° for three participants, mild discomfort after continued use for two participants.
Device cost less than 500 USD [23]	✔, *Partially meets specification:*: Components cost 160 USD, cost to users not evaluated
Able to don on flexed and flaccid hands in under 5 minutes, ideally without assistance [8]	✔, *Meets specification*: Each user donned the glove onto their spastic (flexed) or flaccid hand in under 3 minutes and doffed it in less than 1 minute. Assistance was needed since the wrist strap was difficult to tighten.
Enables stroke survivors with severe hand impairment to extend their fingers [8, 23]	✔, *Meets specification*: Increased finger extension for each stroke survivor.
Enables stroke survivors to use their affected hand in activities of daily living [8, 20, 23, 44]	~, *Partially meets specification*: Increased BBT scores for each stroke survivor and enabled 3 of 5 participants to better grasp, manipulate and release a water bottle.
Additional HERO Glove Specifications	
Length x Width	23cm x 10cm
Safety Features	Screw-drive transmission to limit extension, Velcro wrist strap for doffing in less than 1 minute
Actuated ROM	Approximately 270° (finger length dependent)
Speed of Actuation	Approximately 35°/s (summed MCP-PIP-DIP bending)
Battery Life	>2 hours of continuous use

*The ✔ denotes "Meets specification", ~ denotes "Partially meets specification", and **X** denotes "Does not meet specification".

the dorsal actuator; however, this will reduce the extension produced for individuals with high tone. Currently, the ring and little fingers are gloved only for aesthetics. Second, the palm of the glove, the wrist brace and the palmar actuator were removed to make the glove easier to put on, as in Yap *et al.* [23] and Polygerinos *et al.* [30], once it was discovered that the dorsal cable ties could provide some flexion assistance, similar to Nycz *et al.* [26] and Gandolla *et al.* [31].

This modification was necessary because the stroke survivors required 15 minutes of assistance to put on the intermediate prototype and this was deemed unacceptable for in clinic or at home use. Removing these components also reduced the size, weight and cost of the glove and exposed the user's palm to avoid blocking sensation. The design tradeoff was that the intermediate prototype produced over 2N of pinch force and 17N of grip force for the four able-bodied participants with their hands relaxed, while the HERO Glove moved the relaxed hand into a pinch posture but did not generate force. It was assumed that the stroke survivors' tone could stabilize objects so easing the donning process was a higher priority than assisting grip strength. Third, the automated control mode was developed because the participants had difficulty pressing the physical button while supporting the arm.

D. Participant Recruitment

Observational case studies with stroke participants with limited active finger extension were completed to evaluate the HERO Glove's efficacy in assisting motion and enhancing task performance. A convenience sample of stroke survivors was recruited by therapist referral for outpatients and the TRI-UHN central recruitment process for inpatients. This study was approved by the UHN Institutional Review Board and each participant provided informed consent to participate in the study. Researchers administered the study methods for all stroke survivors, after being trained by an occupational therapist. Outpatients did not receive therapy prior to the study. Inpatients completed scheduled therapy sessions on the same day as the study.

Inclusion Criteria:

- Stroke survivors more than 1 week post-stroke
- Chedoke-McMaster Stroke Assessment Stage of the Hand (CMSA-Hand) [27] between 1 and 4, inclusive (moderate to severe hand impairment)
- Less than 45° of active extension in the index finger proximal interphalangeal (PIP) joint, measured using a finger goniometer
- Greater than 45° of passive extension in the index finger PIP joint, measured using a finger goniometer
- Numeric Pain Rating Scale (NPRS) score between 0 and 4, inclusive, after active and passive finger flexion and extension
- No severe risk for skin breakdown under applied loads
- No Botulinum Type A Toxin (Botox) injections in the hand within the last 3 months

Only the PIP joint was measured to reduce the participants' screening time commitment and because stroke survivors move this finger joint the least, compared to able-bodied participants, while grasping [32].

E. Assessments

1) Range of Motion, Tone and Spasticity: The stroke participants were seated with their hand and arm resting on a table at approximately elbow height. The researcher measured the bend angle of the index finger metacarpophalangeal (MCP), PIP, and distal interphalangeal (DIP) joints using a finger goniometer (JAMAR) in four positions, passive extension, active flexion, active extension and then passive flexion. Only the index finger was measured in order to minimize the length of each study session. The term "passive" refers to when the participant was asked to relax their hand for the researcher to move and "active" refers to when the participant was asked to extend or flex their fingers without assistance. Active extension was calculated by summing the joint angles at active extension. Passive ROM was calculated by subtracting the passive extension joint angles from the passive flexion joint angles. Active ROM was calculated by subtracting the active extension joint angles from the active flexion joint angles. Further ROM measurement and calculation details are shown in Supplementary Figure 3. The finger joints were not extended past straight to avoid potential injury so the maximum extension was 0° for each joint. The fingers were flexed by the researcher until the fingertip met the palm near the MCP joint. The researcher stopped applying force if it was painful to the participant. Tone and spasticity in the index finger was assessed during the passive extension measurements using the Modified Modified Ashworth Scale (MMAS) [28] and Modified Tardieu Scale (MTS) [33].

The robot-assisted ROM was measured using the same instruments, arm posture and finger joints as in the unassisted ROM measurements. The glove was donned with assistance to ensure proper alignment and the robot extended the fingers to ensure safe operation. Then the participants were asked to keep their hand relaxed or to flex or extend their hand as the robot assisted their motion. The researchers measured the finger joint bend angles in four positions, relaxed-hand robot-assisted flexion, flexed-hand robot-assisted flexion, relaxed-hand robot-assisted extension, and then extended-hand robot-assisted extension. The extended-hand robot-assisted extension joint angles were subtracted from the flexed-hand robot-assisted flexion joint angles to calculate the robot-assisted ROM (R-A ROM). The relaxed-hand measurements were not used because the robot is intended to assist the participants' residual abilities as an assistive and rehabilitative device.

2) Grip and Pinch Strength: The participants' grip and pinch strengths were measured using a dynamometer and pinch gauge (JAMAR) with sensitivities of 1kg and 0.5kg. The participants' fingers were positioned around each gauge with the arm resting on the table. The researcher supported the gauge and asked the participant to grip and pinch with their maximum strength.

Robot-assisted grip and pinch strength was first measured while the participants were asked to keep their hand relaxed to allow the robot to deliver the grip and pinch force. Then the participants were asked to flex their hand to provide additional grip and pinch force. The flexed-hand grip and pinch forces were used for the robot-assisted grip and pinch strength results. Strength and ROM measurements were added to the study protocol after P1.

3) Box and Block Test: The Box and Block Test (BBT) is a test of participants' capability to grasp 2cm x 2cm

TABLE II
STROKE PARTICIPANT DEMOGRAPHICS AND HAND FUNCTION

	Months Post Stroke	CMSA Hand	MMAS	FMA-S	Aff / Dom Hand	Gender	Age
P1	57	1	1	0	R/R	M	72
P2	0	1	1	0	R/R	F	80
P3	86	3	0	2	L/R	M	57
P4	0	1	0	1	R/R	F	83
P5	306	3	2	1	L/R	F	70

wooden blocks, lift them across a 15.2cm barrier at their midline, and release the blocks, in one minute [29]. On average, able-bodied subjects over 75 years of age can transfer more than 60 blocks [34]. This test has been used to evaluate a previous robotic hand orthosis [30]. Participants who are able to perform the BBT may also be able to perform daily tasks with similar sized items, such as utensils, toothbrushes and handles. Participants were asked to perform this task without robot assistance and with the HERO Glove in both the button-press and automated mode. Participants were given up to three minutes to practice the task before being evaluated.

4) Chedoke Arm and Hand Activity Inventory – Water Bottle Task: The water bottle grasp task, an ADL, was assessed using the Chedoke Arm and Hand Activity Inventory (CAHAI) scale from 1 (unable to perform task) to 7 (able to perform the task independently and quickly without assistance from the unaffected hand) [35]. Participants were seated with their hand resting on a table and a water bottle placed approximately 20cm in front of their torso. Participants were instructed to reach with their affected arm to grasp the water bottle, lift the water bottle and hold the water bottle while twisting off the lid with the opposite hand. Arm assistance was provided by the researcher or the unaffected side if needed. An empty plastic water bottle was used as opposed to the coffee jar recommended for the CAHAI, because it was safer to drop, easily accessible, of comparable diameter (76mm), and light enough to lift with a weak but active arm.

III. STUDY RESULTS

A. Participants

This study involved five acute and chronic stroke survivors with a broad range of severe hand impairments, as presented in Table II. The study results for ROM and task performance are shown in Tables III and IV. The grip and pinch strength results are shown in Supplementary Table II. The participants ranged from CMSA-Hand level 1 (flaccid paralysis) to 3 (able to flex but not extend the fingers). Tone and spasticity (restriction to assisted finger extension) was measured using the MMAS and MTS and ranged from 0 (no increase in tone) to 2 (more marked increase in tone), with no score differences between the two measures. Four of five participants showed a reduced sense of touch in their fingers, palm and forearm, using the Fugl-Meyer Assessment - Sensation to Light

Touch (FMA-S) [36]. Extra caution was taken to check for redness and marks on the skin in these cases. No participants reported pain while moving the joints, as assessed using the Numeric Pain Rating Scale.

B. Unassisted Range of Motion and Strength

The researcher was able to fully straighten the index finger MCP, PIP and DIP joints for all participants except P2 and P5. Their MCP and DIP joints did not resist extension, but their PIP joints resisted extension at the end range for P2 and throughout the range of motion for P5. For all participants, the finger was able to be fully bent so the fingertip touched the palm. Active ROM was not visible in any finger (or thumb) for three participants (P1, P2, P4). P3 could flex and extend each finger except the thumb and index finger PIP joint. P5 could modulate grip force to demonstrate a small active range of motion. Grip strength was not existent in four of five stroke participants. Pinch strength was not detected in three of five stroke participants and was measured using a tripod pinch for all participants except P5, whose lateral pinch strength was measured because the fingers could not be oriented properly for a tripod pinch.

C. Robot-Assisted Range of Motion and Strength

The HERO Glove was effective in assisting the stroke survivors' motion. Each participant showed greater index finger extension (nearer to 0°) with robot assistance than without robot assistance (increase of 97.5°, SD 24.0, p<0.01). A similar increase in thumb and middle finger extension was observed for all stroke survivors. The robot-assisted ROM was larger than the active (unassisted) ROM for three of four stroke survivors (increase of 46.3°, SD 65.5). This result was not significant due to the low sample size and because P3 was able to form a tighter fist when not wearing the glove. The Percent of Motion Restored (%MR) metric is proposed in Eq. 1 for evaluating how well the robot achieves the goal of restoring the participants' passive ROM. This metric compares the robot-assisted ROM to the active ROM and is normalized by the difference between the passive and active ROM so that robots can be compared evenly if the participants' residual abilities vary between samples.

$$\frac{(robot\ assited\ active\ ROM - active\ ROM)}{(passive\ ROM - active\ ROM)}$$
$$= \%PROM\ Recovered \quad (1)$$

The HERO Glove's assistance restored a portion of the passive ROM for three of four participants (20.4%MR, SD 32.5). The largest increases in extension and %MR were observed at the joints with the least active motion and tone. Participants with toned (clenched) hands experienced increases in extension at the MCP and DIP joints and the PIP joint remained mostly immobile. The actuator fully extended and contracted for each participant. For participants P2, P4 and P5, the robot-assisted ROM was equal to the relaxed-hand robot-assisted ROM because these participants' lacked active finger motion. P3's robot-assisted ROM was 15° larger than his robot-assisted

TABLE III
INDEX FINGER EXTENSION AND RANGE OF MOTION (ROM) ASSESSMENTS WITH AND WITHOUT ROBOT ASSISTANCE (R-A)

Participant	Active Extension	R-A Extension	Extension Increase	Passive ROM	Active ROM	R-A ROM	% of Motion Restored	ROM Increase
P1	120° (90:30:0)	n/a	n/a	280° (105:125:50) - (0:0:0)	0° (90:30:0) - (90:30:0)	n/a	n/a	n/a
P2	160° (15:100:45)	40° (10:30:0)	120°	210° (70:100:70) - (0:30:0)	0° (15:100:45) - (15:100:45)	70° (30:70:10) - (10:30:0)	33.3	70°
P3	130° (40:60:30)	60° (0:60:0)	70°	265° (75:110:80) - (0:0:0)	125° (85:110:60) - (40:60:30)	90° (40:110:0) - (0:60:0)	-25.0	-35°
P4	115° (70:30:15)	0° (0:0:0)	115°	235° (90:100:45) - (0:0:0)	0° (70:30:15) - (70:30:15)	120° (30:60:30) - (0:0:0)	51.1	120°
P5	170° (50:90:30)	85° (0:85:0)	85°	140° (70:110:35) - (0:75:0)	5° (50:95:30) - (50:90:30)	35° (0:120:0) - (0:85:0)	22.2	30°
Mean (SD)			97.5° (24.0) p=0.0002				20.4% (32.5)	46.3° (65.5)

The participants' index finger (MCP: PIP: DIP) joint angles were measured during passive extension, active flexion, active extension, and passive flexion, followed by robot-assisted flexion and robot-assisted extension. Further measurement terminology description is provided in Supplementary Figure 3. The more fully the index finger extended the lower the finger joint bend angle. Finger joints that were fully extended (or hyper-extended) were measured as 0°. After P1, measuring joint angles while wearing the glove was added to the study protocol.

TABLE IV
TASK-BASED ASSESSMENTS WITH AND WITHOUT ROBOT ASSISTANCE (R-A)

Participant	Box & Block Test	R-A Box & Block Test - Button Mode	Box & Block Test Increase	R-A Box & Block Test - Auto Mode	CAHAI – Water Bottle Task (WBT)	R-A CAHAI – WBT – Button Mode	CAHAI – WBT Increase
P1	0	5	5	2	1	2	1
P2	0	2	2	n/a	1	2	1
P3	2	4	2	2	4	4	0
P4	0	2	2	n/a	1	1	0
P5	0	3	3	3, with arm assistance	1	3	2
Mean (SD)			2.8 (1.3), p=0.004				0.8 (0.84)

relaxed-hand ROM because his residual grip strength allowed him to further flex his MCP joint. The glove provided minor obstructions to measuring joint angles; however, this was a more robust approach than the optical tracking system used in preliminary testing, due to the small distance between joints, occlusion caused by other fingers and detachment of markers from the skin. The robot's flexible structure relied on the participants' anatomy to restrict over-extension. The robot extended the DIP joint past straight for three participants because their PIP joints resisted extension while their DIP joints were flaccid. No participants reported pain from this motion. Two participants reported mild pain, NPRS 1-2 (out of 10), on the dorsal side of the index finger's proximal phalange after more than thirty minutes of use that resolved with rest.

The robot's assistance did not enhance the participants' grip or pinch strength. The flexible structure of the robot caused the fingers and thumb to divert from the reaction force of the dynamometer and pinch gauge. Instead of applying force through the MCP joint, the PIP and DIP joints curled around the dynamometer and deflected off the pinch gauge.

D. Unassisted Box & Block Test Performance

Three of five participants required support from their unaffected hand to move their hand into the box. Four of five participants could not grasp any blocks with their affected hand. P3 transferred two blocks in one minute using the little finger.

E. Robot-Assisted Box & Block Test Performance

The HERO Glove enabled stroke survivors to incorporate their affected hand into the BBT and water bottle task, as shown in Fig. 2, Fig. 3 and Table IV. The HERO Glove enabled each participant to create space between the fingers and the thumb during extension and then touch their index finger to their thumb, to create a tripod pinch for four participants and a lateral pinch for P5. This assistance improved each participant's performance in grasping and transferring blocks with the HERO Glove (2.8 block increase, SD 1.3, p<0.01). Since each participant had an inability to lift their affected arm for one minute the researcher supported and positioned the forearm. The glove did not fully extend toned hands so the researcher operated the physical button, knowing when the

Fig. 2.   The HERO Glove enabled stroke participants to transfer blocks during the Box and Block Test. The left figure demonstrates P1 attempting unsuccessfully to grasp a block with the affected hand, while supporting the arm with the other hand. The two figures on the right demonstrate P1 completing this block grasp and transfer task independently with the HERO Glove providing extension and flexion assistance automatically.

Fig. 3.   Five stroke survivors with severe hand impairments evaluated the HERO Glove's assistive capabiltities. The top images show the hand impairments of P1 through P5, respectively. The bottom images show how the HERO Glove was worn and operated by P1 through P5, respectively, to perform tasks independently. The HERO Glove's assistance enabled P3 and P5 to extend their fingers and thumb around the water bottle. The HERO Glove's assistance extended and flexed P1, P2 and P4's fully paralyzed hands to grasp the water bottle and blocks independently.

hand was best-oriented for the grasp. Then each participant trialed the manual and automated modes and supported their forearm with their unaffected hand. Each participant was able to control the robot's assistance in both the button-press and automated modes. P2, P4 and P5 did not trial the automated mode independently during the BBT because they were unable to move their affected arm with the accuracy required position their fingers around the blocks. P1 and P3 were able to use the HERO Glove in the automated mode to each grasp and transfer two blocks in one minute independently. P1 required the automated mode because it was difficult to press the button while supporting the full weight of his flaccid arm. P3 transferred five blocks independently in the button-press mode and preferred this mode to the automatic mode for its reliability and switching speed. P5 transferred three blocks in the automated mode, with the researcher supporting her forearm. The automated mode functioned perfectly for P1, P3 and P5, as all seven grasps and seven extensions required to transfer the seven blocks occurred when desired and without added delay or early release of blocks (0% false positives, 0% false negatives). All participants were experiencing global and muscular fatigue by one hour into the study so the BBT trials were not repeated.

F. Unassisted Water Bottle Task Performance

No participants could complete the water bottle ADL task without the unaffected hand supporting the affected hand. Only P3 and P5 had some capacity to reach with their affected arm, although limited due to weakness. P5 could not extend the fingers enough to press the water bottle into the affected hand. P1, P2, and P4 did not have the grip strength required to hold the water bottle while lifting or twisting the lid. P3 required assistance from the other hand to stretch the affected fingers and then quickly press the water bottle into the affected hand. P3 could then hold and lift the water bottle while removing the lid without assistance.

G. Robot-Assisted Water Bottle Task Performance

The water bottle task demonstrated the HERO Glove's assistive capabilities and areas for design improvement. P1, P2, and P5 showed improved performance, as assessed using the CAHAI scale, with the HERO Glove enabling them to extend their fingers and place the water bottle in their hand. The glove enabled them to hold the water bottle during lifting and lid twisting. The CAHAI scores for P3 and P4 did not change because the glove did not provide enough thumb extension

for P3 to complete the grasp unassisted or enough force for P4 to hold the water bottle while twisting off the lid. The water bottle task was trained using a hand-over-hand technique for less than three minutes and was assessed while the stroke survivors performed the task independently in the button-press mode. P3 successfully used the automated mode to trigger extension and flexion to grasp, lift, lower and release the water bottle. The lid was not removed because lifting then stopping caused the glove to release the water bottle. The automated mode was not tested with the other participants due to arm fatigue from the prior assessments. The HERO Glove's weight did not affect P3 or P5's ability to reach and lift their arms while holding the water bottle.

H. Usability Observations With the HERO Glove

The stroke participants and occupational therapists were informally questioned about the glove's usability after the trials. Table I summarizes how well the HERO Glove met their requested specifications. They expressed satisfaction with the HERO Glove's motivations as an assistive and rehabilitative device for performing daily tasks more easily and independently and reintegrating the affected hand. Their satisfaction with its portability, light weight such that it did not affect arm motion or fatigue, ease of donning, set up and use and potential affordability provided justification for the untethered design. They commented that the grip strength should be improved, an arm support should be available, and the construction should be more comfortable, robust and aesthetically-pleasing for the stroke survivors to use the HERO Glove during daily tasks at home.

IV. Discussion

Robotic hand orthoses have the potential to enable stroke survivors to generate larger motions and stronger forces. This can enable stroke survivors to more usefully incorporate their affected hand into activities of daily living that would otherwise require compensatory strategies and caregiver support. We iteratively designed a novel robotic hand orthosis and control strategy with occupational therapists and stroke survivors based on their specified requirements. Key novel features of the HERO Glove are:

- The robot is untethered and fully contained on the hand, including the mechanism, actuator, electronics and battery. This minimizes the number of donning steps and makes the device wireless and convenient to use when sitting, standing and transferring.
- The buckling-resistant dorsal cable ties are coupled to a single motor to provide strong extension assistance and some flexion assistance. This enables the HERO Glove to be more affordable for stroke survivors, have an open-palm to ease donning on a flexed hand and possess the lowest overall weight among wearable robotic hand orthoses to minimize arm fatigue.
- The use of an IMU to measure the user's arm and wrist motion and use this signal to trigger robotic assistance. This enables stroke survivors with severe hand impairment to control the HERO Glove without their unaffected hand.

The HERO Glove's assistive capacity was evaluated with five stroke survivors with severe hand impairment and provides evidence of its efficacy by demonstrating a:

- Statistically significant increase in index finger extension for stroke survivors with flaccid and toned hands.
- A statistically significant improvement in performance on a functional task, the BBT, and improvement for most participants in ROM and on an ADL, the water bottle task.

This work also provides design guidance for further wearable hand robot development through the requirements suggested by therapists and stroke survivors and observations on how well five stroke survivors with severe hand impairment used the HERO Glove in manual and automated control modes, as summarized in Table I. In its current development stage, the HERO Glove can help stroke survivors with specific hand impairments perform daily tasks, such as holding bowls, containers and pans that require object stabilization but not lifting. The HERO Glove should provide greater grip strength through the fingers and thumb to enable individuals with weak grip strength to independently perform daily activities safely.

A. Impact of Mechanical Design on Task Performance

The HERO Glove accomplished its main objective of increasing finger extension so stroke survivors with severe hand impairments could grasp daily objects. The cable tie tendons applied a strong force to extend high-tone fingers, which has proven to be difficult for previous robots [20], [21]. The glove extended the DIP and MCP joints fully for each participant; however, the stroke survivors with high finger tone also desired full restoration of extension at their stiffest joint, the PIP joint. The challenge for increasing this extension is in creating a mounting point on the glove that mounts the single actuator as rigidly as a wrist brace with distributed actuators, as in Fischer *et al.* [12]. In addition, the spacing between cable guides should be reduced to block hyperextension and further distribute pressure, as in [12] and Rose and O'Malley [37]. Once the glove was removed, the hand was less toned and more extended, which may motivate spontaneous unassisted hand use.

All participants with flaccid hands and one participant with a toned hand could not produce a strong grip force. With a passive dynamic orthosis these participants would not have been able to overcome the extension bias force, leading to poorer task performance [38]–[40]. In contrast, the HERO Glove's actuator contracts to release the extension force and assist the fingers to flex, increasing their ROM. In addition, quantifying how well the assistance increases survivors' finger extension and active ROM at a joint level provides a more specific benchmark for future hand robot evaluations than the FMA-UE [20]. Stronger grip force is required to improve task performance. Methods for integrating flexor tendons and donning the HERO Glove independently should be investigated, such as routing the tendons dorsally or attaching the tendons with buckles or ratchets once the fingers are extended [37], [41], [42].

The HERO Glove is the first wearable hand robot to show that its assistive capacity enhances BBT performance for stroke survivors. The HERO Glove is untethered, which differentiates it from previous wearable hand robots that improved block grasping for spinal cord injury and muscular dystrophy, but required wheelchair-mounted actuation units [22], [25], [43]. This study extends current evidence that untethered wearable hand robots can effectively assist stroke survivors' cylindrical grasp [20], [44], by demonstrating that three stroke survivors were only able to perform the water bottle task with the HERO Glove's assistance. Performance could be improved by further assisting finger extension, grip strength and thumb abduction and opposition. The actuator could be relocated closer to the thumb to better assist its motion, but this may obstruct wrist motion and affect the glove's aesthetics [12]. Additional studies are required to investigate how well the HERO Glove assists stroke survivors in a variety of activities of daily living, using the CAHAI and Toronto Rehabilitation Institute Hand Function Test [22], [25]. To perform these activities independently, upper-arm neuroprostheses like exoskeletons, gravity supports and neuromuscular stimulators may be necessary because each stroke participant showed significant weakness in shoulder flexion and elbow extension and fatigued quickly.

B. Usability Perspectives of Therapists and Stroke Survivors

The overarching goal of this iterative design process was to create a wearable hand robot that met therapists' and stroke survivors' requirements so the robot would be easy to integrate into therapy practice and daily routines. To meet this need, we created a portable, easy to use and affordable device that enables stroke survivors with low-functioning hands to practice higher level tasks that are more similar to their daily tasks. The therapists were interested in using the HERO Glove to practice more engaging real-world activities with their clients. They suggested that the glove could help clients adhere to the forced-use component within programs like constraint-induced movement therapy [45]. The HERO Glove is currently suitable for stroke survivors, CMSA-Hand <4, that require greater finger extension and flexion in order to work towards their therapy goals in the clinic. Before the HERO Glove is ready for home use, further design is required to block hyperextension, distribute pressure and replace glued areas with bolts and sewn on enclosures that protect the wires and mechanism from impact, snagging and continuous wear. In addition, the therapists requested improved assistive capabilities, especially for grip strength and arm support, so they would have more flexibility in selecting tasks that align with their clients' goals.

The button-press mode was reliable and easy to understand with little training. The therapists and stroke survivors voiced that the automated mode was important because it kept the unaffected hand free and could motivate spontaneous arm use. The current algorithm is useful for pick-and-place exercises but the algorithm needs to be as reliable as the button-press mode to give users confidence in spontaneously using their arm during daily use without dropping breakable objects.

Given the low false negative and positive rates demonstrated in the BBT, the low cost and size of IMUs and the infancy of IMU-triggered orthoses, there is an opportunity and motivation to improve algorithm reliability. Insight can be gained from Bennett and Goldfarb [46], where a non-synergistic movement (shoulder abduction) was used to intuitively control a prosthetic wrist's pronation velocity. Participants could also be trained to cancel misfires by shaking their hand, similar to how electrooculography has been used [25]. Machine learning approaches could be used to fuse IMU data with force, vision, voice, EMG and EEG data to improve reliability and add dexterity and grasp force modulation for higher degree-of-freedom exoskeletons.

A main constraint for this design was the need to keep the material cost affordable so the device could more likely be accessed by stroke survivors without comprehensive health insurance coverage. The design incorporates only one actuator, minimal sensors and low-cost components to keep the cost within the range specified by stroke survivors [23]. Do-It-Yourself communities could assemble the HERO Glove themselves to minimize manufacturing costs, as is currently managed with elbow exoskeleton kits [47]. Personalizing the glove to the user's hand size and swelling would enhance the glove's ease of donning, comfort and assistive capacity. An actuator with a lower gear ratio that is faster and back-drivable could also be selected if the user does not need a strong extension force. In addition, the IMU control thresholds could be tuned to the individual. Given the diversity in digital literacy, lifestyle and upper extremity function among stroke survivors, multiple designs and adaptive control schemes may be required to serve specific subsets of the stroke population.

C. Study Limitations

This paper presents the HERO Glove design and an observational clinical pilot study evaluating its assistive efficacy. The diversity of experience within our design team and the rolling recruitment method allowed us to understand the complexities of two stroke survivors' hand impairment and revise the glove's structure, form, fit and control to meet future participants' hand assistance needs. Limitations of this study design are that the statistical power is low and the solution may not be effective for stroke survivors with only mild to moderate hand impairment.

In future study designs it would be useful to have the same participants return to test device iterations to validate the usefulness of the modifications. This would also allow us to perform repeat trials and quantitative experiments on ROM of the thumb and other fingers, muscle activity and holding force before the participant experiences fatigue. Collecting the IMU data would also be useful for quantifying arm motion; however, firmware updates are required to transmit the data via Bluetooth without delaying the automated control mode. Usability feedback from our participants and stroke working group provided an understanding of their experiences with the HERO Glove, but usability questionnaires, such as the Psychosocial Impact of Assistive Devices Scale (PIADS) [40] or Usefulness, Satisfaction and Ease of Use

questionnaire [23], and semi-structured interviews are required to provide structured design guidance.

V. FUTURE WORK

Key lessons learned through this study were that therapists and stroke survivors can play a vital role in tailoring the device's usability and stroke survivors are interested in using wearable hand robots to assist their affected hand to perform daily tasks independently. There is a strong need to design and evaluate these robots with a greater number and variety of people with neurologically-affected hands. This will help refine design specifications to improve their assistive and rehabilitative efficacy, as currently no robots can be used independently or enable affected hands to perform activities of daily living as functionally or quickly as unaffected hands. Once the HERO Glove is sufficiently advanced to satisfy stroke survivors ADL needs, we will be able to study how well its assistance can be integrated into a home therapy program to promote neuromuscular recovery. Through the addition of data storage and a mobile application we will be able to monitor their program adherence and recovery and provide feedback to therapists to learn their clients' behavior and adapt their therapy program to meet their changing capacities and needs.

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