

# Improving Grasp Function After Spinal Cord Injury With a Soft Robotic Glove

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**Abstract**—People with tetraplegia resulting from spinal cord injury experience debilitating hand impairments that may lead to lifelong dependence on others to perform activities of daily living. Wearable robotic devices that actively support hand function during daily living tasks could bring great benefits to this population. In this work, the performance of a textile-based soft robotic glove controlled by the user with a button was evaluated in thirteen participants with tetraplegia. Performance outcomes included activities of daily living using the Jebsen Taylor Hand Function Test, active range of motion of the fingers, and grasp strength for power and pinch grasps. In the Jebsen Test, participants showed significant improvements in performance of activities of daily living with glove assistance, completing a median of 50% more tasks than in their baseline attempt without the glove. Significant improvements were also found for power and pinch grasp forces and active range of motion of the fingers with the glove assistance. Participants with lower baseline motor function received greater benefits from glove assistance. This work demonstrates the effectiveness of a user-controlled textile-based soft robotic glove to improve activity of daily living abilities in individuals with hand impairments resulting from spinal cord injury.

**Index Terms**—Spinal cord injury, tetraplegia, soft robotic glove, activities of daily living, hand function assistance.

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## I. INTRODUCTION

EVERY year, over 17,000 Americans suffer a spinal cord injury (SCI). Cervical spinal injuries are the most frequent and severe type of SCI, resulting in partial or total paralysis of all four limbs and trunk, also known as tetraplegia [1]. The loss of hand function is particularly devastating for individuals with tetraplegia, as it strongly affects the ability to self-care and perform activities of daily living (ADLs). The lack of independence in ADLs is associated with decreased life satisfaction and quality of life and reduced life expectancy [2]. Since return of hand function is the highest priority identified in tetraplegia [3] and less than 1% of individuals with SCI regain premorbid mobility status [1], assistive devices that augment hand function are highly desirable [3], [4].

Over the past fifteen years, wearable robotic devices have emerged as an exciting prospect for augmenting and restoring movement. Rigid exoskeletons and robotic orthoses can deliver precision and power to assist motion of different joints [5]–[7]. However, challenges exist with the use of these devices, most namely comfort and portability combined with the need to carefully align the rigid frames of the device with the biological joints [8], [9]. Soft robotic devices and hybrid soft-rigid devices are a promising response to the limitations of rigid systems. By using soft materials such as textiles [10]–[13], elastomers [14] or artificial tendons [15]–[20], these devices can be inherently safe, lightweight, compliant and non-restrictive to movement [21] allowing them to be worn for long periods of time and in different environments, including at home, in clinics or in the community [22].

Several soft robotic gloves have been developed to address rehabilitation and assistance of the hand [23]. While most efforts have focused on the design and actuation of these devices, only a few have progressed to clinical trials [24]–[30], and even fewer have been assessed for ADL assistance following SCI [28], [29]. In previous work, we demonstrated that a pneumatic fabric-based soft robotic glove was able to improve lift force and object manipulation for nine participants with tetraplegia using the Toronto Rehabilitation Institute - Hand Function Test (TRI-HFT) [28]. This soft robotic glove was manually controlled by a researcher during the TRI-HFT and provided assistance via constant curvature bending actuators.

More recently, we developed a new generation of our soft robotic glove with multi-articular textile actuators for improved finger motion and a state-machine controller for

intent detection [29]. Two control strategies were implemented into the glove system to allow voluntary grasping: using the glove's soft sensors or an external button. An initial evaluation using the glove's sensor system showed hand function improvements in three individuals with tetraplegia using a standardized test, despite persisting challenges with the robustness of the sensor connections and trigger accuracy.

In this study, the primary goal was to evaluate the performance of the optimized soft robotic glove in restoring ADLs for individuals with tetraplegia resulting from SCI. Towards this end, thirteen participants were asked to perform the Jebsen-Taylor Hand Function Test (JHFT) three times, once without the glove and twice with the glove powered, controlled by the participant touching a button with the non-gloved hand. Our primary hypothesis was that the glove would improve the ability to perform ADLs over baseline. Secondly, we posited that the glove would increase maximum grasp strength and active range of motion of the fingers.

## II. SOFT ROBOTIC GLOVE: DESIGN AND CONTROL

The pneumatic actuators of the new glove version were designed following the same principles of the previous textile-based glove, evaluated in a pilot study [28]. Each actuator consists of two thermoplastic elastomer balloons inserted between three fabric layers with different material properties – a top layer with high stretch textile and the two bottom layers with stiffer, inextensible fabric. Upon inflation, the upper chamber results in flexion of the actuator and the lower chamber produces extension (Fig. 1).

In the previous glove, the top fabric layer of the actuators was pleated, resulting in constant bending curvature during flexion. In the new actuators, the textile of the top layer is gathered over the location of finger joints, which leads to localized expansion of fabric and actuator bending motion that matches the natural finger flexion. When unpowered, the glove design allows it to be mechanically transparent and low-profile, so that the range of motion is not constrained. The glove is sized to fit a total of four hand sizes, with weights ranging from 122g (small size) to 149g (extra-large), resembling a typical glove for operating a manual wheelchair. To support ease of donning and doffing, a side zipper and a wrist wrap were incorporated.

The glove is powered by a portable pneumatic control box, built purposely as a research platform to allow fast prototyping and adjustment of experimental conditions. A flow PID controller is used to selectively regulate inflation and deflation of the actuators of each finger, allowing the glove to support a variety of hand poses. In the study, the pressure inside the actuators was limited to 25 psi, the inflation rate was set at 20 psi/sec and, to maintain the consistency across subject testing, two predefined grasp types (power and pinch) were used throughout the study. Speedgoat's mobile target machine (Speedgoat GmbH, The MathWorks) programmed with Simulink Real-Time was used for data acquisition and real-time control.

The state-machine controller developed for grasping intent detection includes four states: relaxed, extension, pinch flexion

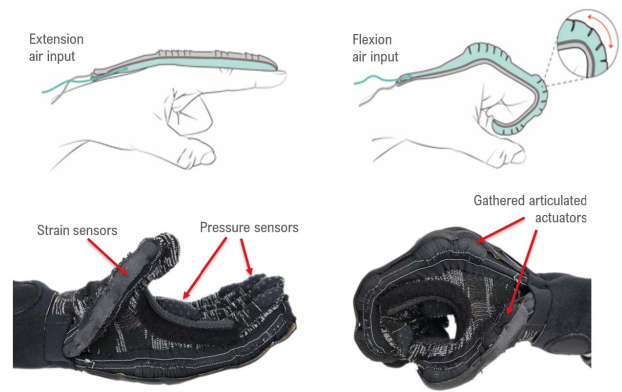


Fig. 1. On top: multi-articulate gathered actuator articulation on finger in extension (left) and flexion (right). Bottom: fully formed custom-knit glove with integrated textile-based pneumatic actuators and soft sensors.

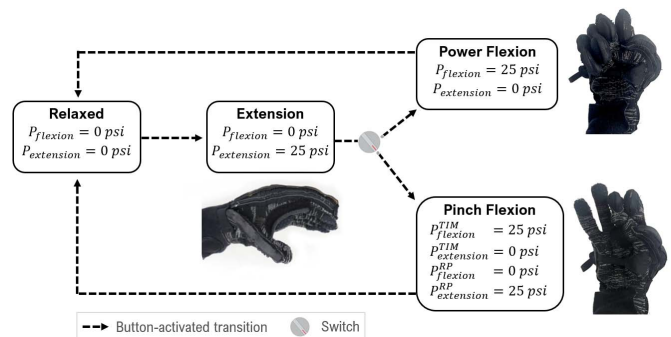


Fig. 2. Four states of the glove's controller. The button makes the glove cycle through extension and flexion (power or pinch) to grasp, and then relaxes to release the item. TIM = thumb, index, middle fingers; RP = ring, pinky fingers.

and power flexion (Fig. 2). By pressing an external button with their non-gloved hand, participants can cycle the glove through the different states in order to grasp. The button can be easily attached to a participant's wheelchair or to a tabletop. Each task was analyzed separately using a single grasp type (power or pinch). Before participants engaged in a task, the grasp type was selected manually using a switch.

## III. GLOVE EVALUATION

### A. Clinical Study Design

Thirteen participants with SCI level C4-C7 were enrolled in a clinical study that followed a one-group repeated measures design. Participants were recruited from rehabilitation centers in the greater Boston area and gave their written informed consent before taking part in the study, approved by the Harvard Medical School Institutional Review Board (IRB13-3418).

The inclusion criteria for the study were: i) being 18-85 years old; ii) scoring 23 or higher on the Mini Mental State Exam (MMSE) [31]; iii) presence of hand function impairment due to SCI that results in difficulty with grasping tasks, range of motion and/or performance of ADLs; iv) presence of SCI motor level between C5 and C7, assessed with the motor portion of the International Standards for Neurological Classification of SCI (ISNCSCI) [32];

v) being fluent in English; and vi) agreeing to photos and videos. The exclusion criteria were: i) having joint stiffness, spasticity or contractures that prevent participation while wearing the device; and ii) having an open wound.

The study was carried out at the Wyss Institute (Cambridge, MA) and Spaulding Rehabilitation Hospital (Boston, MA) for a duration of six months. Each participant was evaluated in a single testing session no longer than three hours.

## B. Experimental Procedures

**1) Baseline Evaluation:** The participants' baseline characteristics were recorded, including their age, gender, time since injury and dominant hand post-injury. The short form of the Neuro-Quality of Life (Neuro-QoL) test for upper extremity fine motor function [33] was performed to gather self-reported levels of ability to perform a subset of ADLs. The Neuro-QoL scores range from 0 to 40, with lower scores indicating greater deficits in ability to perform ADLs.

The upper extremity motor portion of the ISNCSCI was administered by a licensed Occupational Therapist (OT) to evaluate the participants' strength in selected muscles (C5-T1: biceps, wrist extensor, triceps, finger flexor, and small finger abductor) in both upper extremities. For each upper extremity, motor scores range from 0 to 25, with 0 corresponding to total paralysis of all tested muscles and 25 to full active movement of all muscles against resistance. The scores are used to determine the motor level (C5-T1) of each upper extremity according to the ISNCSCI guidelines.

The choice of hand side to test was determined as follows: if the two upper extremities had different motor scores, the tested side was the one with the lowest score – as long as the motor level on that side was not higher than C5; if both sides had the same score, the OT would select the side preferred by the participant for daily use.

**2) Range of Motion and Grasp Strength:** The active range of motion (ROM) of the fingers was measured with a goniometer for the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints of the index finger, and for the MCP joint of the thumb. These joints were selected for their importance in object grasping. For each joint, the maximum active flexion and extension angles were measured at baseline and with powered glove.

The maximum power and pinch grasp strength were measured three times using a flexible pressure sensor mat and then averaged (Fig. 3). The data were recorded with pressure mapping software (MeasureX version 3.6.7, SensorEdge, Parsippany, NJ).

**3) Performance of Activities of Daily Living:** The Jebsen-Taylor Hand Function Test (JHFT) [34] was used to evaluate the ability to perform ADLs at baseline and while wearing the glove powered. This standardized test was chosen because of its good reliability and validity in the SCI population [34], [35], and because of its popular use in comparative studies [27], [36], [37].

The JHFT consists of seven subtests that must be completed as quickly as possible. These subtests include fine motor tasks requiring pinch grasp (writing a 24-letter sentence, turning



Fig. 3. Grasp strength (left) and range of motion measurements (right), using a pressure sensor mat and a goniometer, respectively.

five index cards, picking up six small objects and stacking four checkers) and gross motor tasks requiring power grasp (scooping five beans with a spoon into a can to simulate feeding, lifting five empty cans and lifting five heavy cans of 454 g each). We recorded the number of tasks completed per subset and the time required, with each subtest capped at 120 s according to JTHF instructions [34].

Before the start of the clinical study, additional scoring guidelines for the JHFT were developed to ensure that the evaluation was rigorous and consistent across participants (see Supplementary Materials). These guidelines provided clear-cut solutions for issues prevalent in tetraplegia not covered in the JHFT, such as dropping items or substituting grasp patterns, which were previously identified in the literature [38].

The number of JHFT trials was limited to one baseline trial (BL) and two trials with the glove active (G1 and G2), so that it would fit the available testing time and avoid causing excessive fatigue to the participants. Glove and baseline testing order was randomized to eliminate bias. Before the glove trials, participants were given a 20-minute training period for acquaintance with the glove and the button controller using familiar objects not included in the JHFT. We defined the first glove trial as a warm-up trial and the second as the main outcome for comparison with the baseline trial to allow for participants' adaptation to the glove system.

At the end of the testing session, the participants replied to a usability questionnaire regarding their experience with the glove. The eight-item questionnaire was scored on a 10-point Likert scale ranging from 0 (strongly disagree) to 10 (strongly agree). The times required to don and doff the glove were recorded, as well as whether the participants needed assistance.

## C. Data Analysis

The data collected were analyzed with IBM SPSS (version 25, IBM, Armonk, NY). The normality of variables was assessed through histograms and using the Shapiro-Wilk test. Statistical significance was set at  $p < 0.05$ , and all the tests performed were two-sided.

For the primary endpoint (i.e., changes in JHFT performance between BL, G1 and G2), the two-way Friedman ANOVA by ranks test was used. If significant changes were detected, post-hoc pairwise comparisons using the Wilcoxon signed-rank test were conducted to investigate between which trials these significant changes happened. The Bonferroni



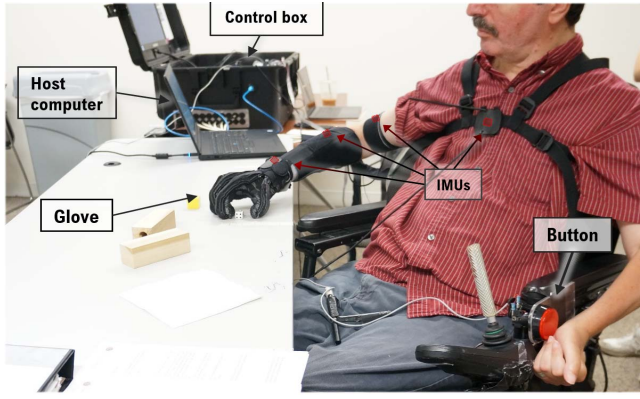


Fig. 4. Experimental setup during the JHFT. Here, a participant sits on his wheelchair and practices grasping with the glove assistance, controlled with the contralateral hand. Data from Inertial Measurement Units (IMUs, not analyzed in this study) were collected and synchronized with video.

correction was then applied to account for multiple group comparisons, and the significance level was set at  $p < 0.017$ . Participants who did not complete all the JHFT trials were excluded from this analysis.

For the secondary endpoints (changes in ROM and grasp strength), if the variables satisfied the assumption of normality, a paired t-test was used to assess whether the mean change from baseline was significant. If the variables did not meet the normality assumption, analysis was performed using the Wilcoxon signed-rank test. Participants who did not complete the measurements in the two conditions were excluded from this analysis portion.

The performance in the JHFT was analyzed for effectiveness and efficiency [39]. Effectiveness reflects the ability to accurately achieve specified goals whereas efficiency is associated with the efforts or resources expended in order to achieve these goals. In the context of the JHFT, effectiveness was measured by calculating the completion rate of each subtest (Eq. 1) and efficiency by the time (in seconds) taken to complete each subtest [40]. For each participant, the mean completion rate and time were the average of the completion rates and times across the seven subtests.

$$\text{Completion rate (\%)} = \frac{\text{Nr items completed}}{\text{Nr items in subtest}} * 100\% \quad (1)$$

## IV. RESULTS

### A. Participants Baseline Characteristics

Thirteen participants with SCI level between C4 and C7 were enrolled in the study (Table I). Two of the participants were unable to complete the three JHFT trials due to poor arm function and inability to control the glove with the button. One participant did not complete all ROM and grasp strength measurements due to an equipment malfunction. These challenges resulted in three sets of participant groups for data processing: grasp strength, ROM – 12 participants, JHFT trials – 11 participants, and usability questionnaire – 13 participants.

The baseline evaluation using the Neuro-QoL test indicated substantial deficits in the ability to perform ADLs, with a

TABLE I  
PARTICIPANTS' DEMOGRAPHIC AND CLINICAL CHARACTERISTICS

Subject	Sex/ Age	Years since injury	Neuro- QoL score	Motor score LUE	Motor score RUE	Tested UE Side	Motor level	Dominant hand post SCI
P1*	M/64	0.8	8	1	3	R	C5	R
P2*†	M/65	51	17	3	4	R	C5	R
P3	M/22	3	13	4	4	R	C5	R
P4	M/34	10	9	4	4	L	C5	L
P5	M/57	4	10	6	6	R	C5	R
P6	M/57	39	14	7	6	R	C5	R
P7	M/62	1	18	7	7	R	C5	L
P8	M/73	9	14	7	21	L	C5	R
P9	F/50	35	18	8	8	R	C6	L
P10	M/32	8	16	8	8	R	C6	R
P11	M/31	8	21	16	13	R	C6	L
P12	M/59	2	13	24	15	R	C6	R
P13	M/64	45	28	17	17	R	C7	R

\* did not complete all JHFT trials; † did not complete grasp strength and ROM measurements. M/F = male/female; R/L = right/left; LUE = left upper extremity; RUE = right upper extremity; UE = upper extremity.

median score of 14 out of 40 across the 13 participants. Likewise, in the upper extremity motor portion of the ISNCSCI test, the median motor score of 7 out of 25 for both upper extremities reflected moderate to severe motor impairments across participants. Note that compared to participants P1-P10, P11-P13 were the highest-functioning ones, with less severe impairments (much higher total motor score) and with some strength for finger flexors (see Supplementary Materials).

For the hand side tested, the ISNCSCI motor level of injury varied across participants, with C5 being the most common injury level (N=8), followed by C6 (N=4) and C7 (N=1).

### B. Glove-Assisted Range of Motion and Grasp Strength

1) *Range of Motion*: The glove led to significant improvements relative to baseline in active range of motion for the MCP and PIP joints of the index finger and for the MCP joint of the thumb across 12 participants (Fig. 5). For the maximum flexion position, there was an average improvement in flexion with the glove of  $20.4^\circ$  [standard deviation (SD) =  $25.6^\circ$ ,  $p = 0.028$ ,  $Z = -2.201$ , Wilcoxon test] for the index MCP joint and of  $14.6^\circ$  [SD =  $20.8^\circ$ ,  $p = 0.034$ ,  $T = -0.361$ , paired t-test] for the thumb MCP joint, both deemed statistically significant. With the glove in extension position, the maximum extension of the index PIP joint improved significantly as well by  $19.6^\circ$  [SD =  $27.3^\circ$ ,  $p = 0.041$ ,  $Z = -2.048$ , Wilcoxon test] in relation to baseline. Overall, the active ROM with the glove was narrower with smaller standard deviation than at baseline, suggesting that the glove's operation range was consistent in assisting finger motion across participants.

In Fig. 5, the mean ROM values measured with and without the glove are compared to functional range of motion (FROM) values from the literature, which represent the minimum ROM necessary to perform ADLs [41]. According to the latter, we see that the glove provided the active flexion needed at both MCP joints exceeding the FROM values, while the PIP joint would need  $30^\circ$  of extra flexion to meet the minimum

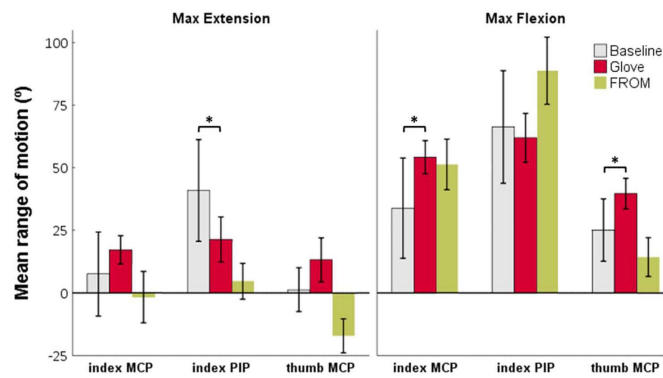


Fig. 5. Mean range of motion across 12 participants for maximum active flexion and extension of 3 finger joints measured at baseline and with glove, and comparison with FROM values. Error bars:  $\pm$  SD. \*  $P < 0.05$ .

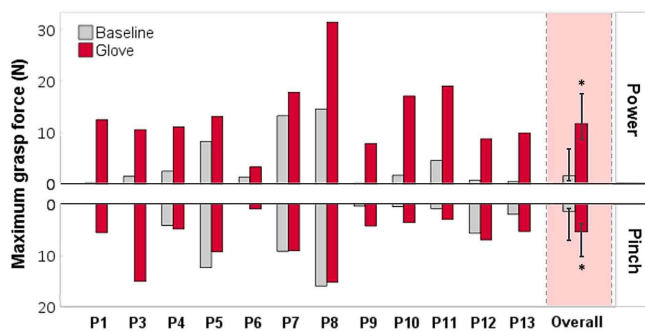


Fig. 6. Maximum grasp strength for power and pinch grasp measured across 12 participants and overall median values, at baseline and with the glove powered. Error bars: 95% confidence interval (CI). \*  $P < 0.05$ .

requirement for ADLs. Note that in the extension position, the glove did not fully extend the fingers to  $0^\circ$  at the MCP or PIP, but rather maintained slight flexion as a design feature to prevent overstretching of the tendons, such that the users would retain full tenodesis capabilities at baseline. (Tenodesis is a naturally-occurring mechanism that passively closes the fingers when the wrist is brought back into extension. This mechanism can be disrupted if the fingers are repeatedly hyperextended, making grasping objects more difficult.)

**2) Grasp Strength:** For healthy adults, the minimum grasp force expected would be 120 N for a palmar grasp and 53 N for pinch grasp [42]. Across the 12 participants, the median maximum grasp force at baseline was 1.5 N for both grasp types, reflecting the severe hand weakness condition affecting these participants (Fig. 6). With glove assistance, the maximum grasp strength increased significantly for power grasp [ $p = 0.002$ ,  $Z = -3.059$ , Wilcoxon test] and pinch grasp [ $p = 0.034$ ,  $Z = -2.118$ , Wilcoxon test] by an average of  $9.5 \pm 4.6$  N and  $2.7 \pm 4.5$  N, respectively.

For power grasps, the median grasp force with the glove of 11.7 N (1.2 kg) is comparable with forces provided by other devices and sufficient for holding everyday objects, which may be otherwise impossible for someone with tetraplegia [23], [43].

For pinch grasps, the median pinch force with the glove of 5.5 N (0.6 kg) is much higher than the forces required for

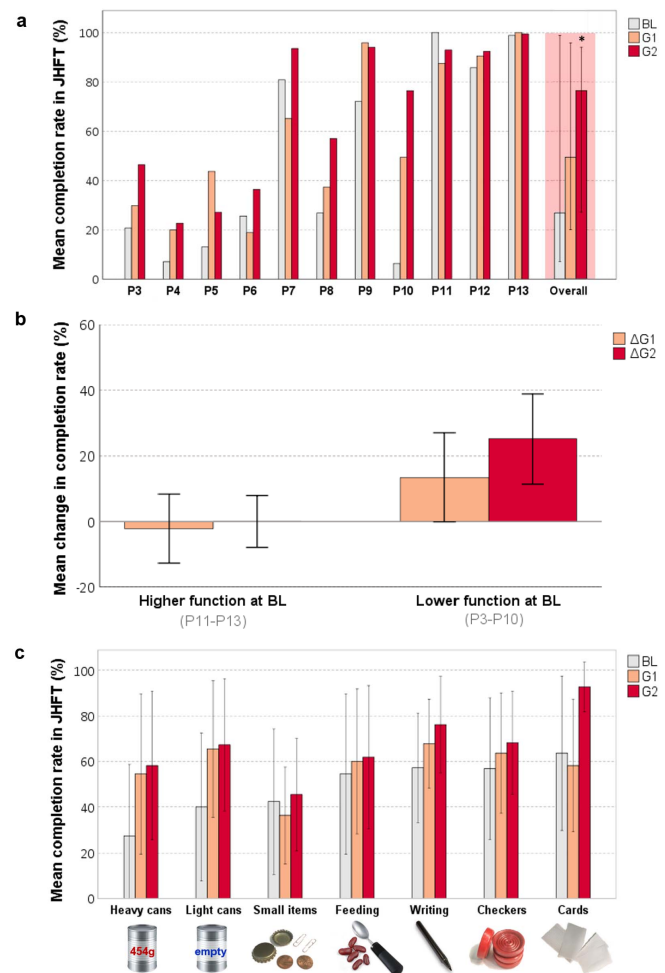


Fig. 7. (a) Mean completion rate in the JHFT across participants for BL, G1 and G2, and overall median values for each condition. \*  $P < 0.017$ . (b) Mean changes in completion rate from BL to G1 and G2, for lower vs. higher-functioning participants. (c) Mean completion rate for each of the 7 JHFT subtests, for BL, G1 and G2. Error bars: 95% CI.

holding the items in our study, and they are also within the same range as the pinch forces needed for different ADLs in other studies [44].

### C. Performance of ADLs With Glove Powered

**1) Effectiveness:** The JHFT performance at baseline revealed substantial deficits in the ability to perform ADLs across 11 participants, with a median completion rate lower than 30% (Fig. 7.A). The completion rate values at BL ranged from 6.4% to 100%, indicating great differences in functional capacity across this group of participants with varying SCI motor levels. Whereas most participants were incapable of completing all the subtests in the JHFT, the highest-functioning ones could perform nearly all tasks without glove assistance. Overall, compared to baseline, participants were significantly more effective in the JHFT with glove assistance, after performing one warm-up trial with the glove [ $p = 0.008$ ,  $Z = -2.667$ , BL vs. G2 post-hoc pairwise comparison with Wilcoxon test]. The median completion rate in G2 was 76.4% [Interquartile Range (IQR): 36.4 – 93.5%],

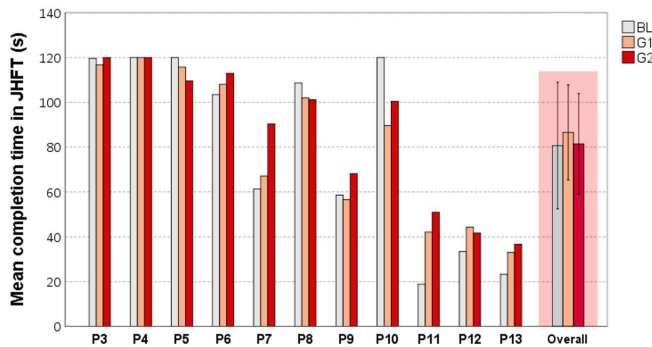


Fig. 8. Mean time in seconds to complete the JHFT across 11 participants for BL, G1 and G2. The overall mean completion time across participants for each condition are presented. Error bars: 95% CI for the mean.

reflecting a 49.6% improvement from baseline in percentage of tasks completed.

The changes in completion rate with glove assistance were notably smaller for the highest-functioning participants (P11-P13, mean change of  $0.03 \pm 6.9\%$  in  $\Delta$  G2), as they required little to no assistance in the JHFT. For the lower-functioning participants (P3-P10), the average improvement in completion rate was of  $25.1 \pm 19.4\%$  in G2 (Fig. 7.B). The high standard deviations are due to the large variability between participants' responses to the glove assistance.

With the glove, in G2, participants on average completed a greater number of items than at BL for all the 7 subtests (Fig. 7.C). The greatest improvements were verified for the tasks of lifting heavy cans, turning index cards and lifting light cans (29-31%), followed then by writing and stacking checkers (11-19%). The smallest improvements were observed for simulated feeding and picking up small objects (3-7%).

**2) Efficiency:** At baseline, participants took on average  $80.6 \pm 42$  s to perform each JHFT subtest, which reflects both the difficulties experienced with grasping and the inability to complete each subtest within the time limit (Fig. 8). While there was variability in baseline function as measured by the JHFT, even the participants with the highest baseline scores were slower than expected for healthy individuals (i.e., mean completion time of 7.1 s for a 60-94 year-old man and 5.4 s for a 20-59 year-old woman/man [34]).

No statistically significant changes in mean completion time were detected across the three JHFT trials performed, meaning that the timing in performance was not noticeably changed with or without the glove. In fact, compared to baseline, participants were on average just 5.9 s [SD = 15.7 s] slower in G1 and 0.7 s [SD = 13.4 s] slower in G2. From G1 to G2, there was a mean improvement of 5.1 s [SD = 8.1 s] in average time to complete the JHFT. Between the two groups of participants with distinct motor function deficits, a great contrast in completion time was verified as well. Whereas the lower-functioning participants were on average 4.5 s [SD = 11.3 s] faster than baseline in the second glove trial, the higher-functioning individuals were slowed down by the glove by 14.6 s [SD = 7.5 s].

TABLE II  
MEDIAN SCORES IN USABILITY QUESTIONNAIRE (N=13)

Usability questions	Median score (IQR)
1. I am truly interested in wearing a device that assists with hand function	10 (8 – 10)
2. I found this glove to be comfortable	9 (7.5 – 9.5)
3. I found this glove easy to pick up items	6 (4.5 – 7)
4. I felt like my grip strength was better with the glove on	9 (7 – 10)
5. I would want to wear this glove to complete tasks in my daily life	8 (4.5 – 9.5)
6. Overall, I am satisfied with my experience with this glove	7 (4 – 9)
7. I would use this glove inside the home	9 (7.5 – 10)
8. I would use this glove outside the home	7 (5.5 – 9.5)

## V. DISCUSSION

The present study focused on the evaluation of a textile-based soft robotic glove to assist hand function during performance of ADLs for individuals with hand paralysis resulting from a cervical SCI. Eleven participants with SCI and different functional status and self-care ability performed the JHFT three times in the same testing session: once at baseline and twice wearing the glove powered, controlled via a button by the contralateral hand. The results in the JHFT demonstrated significant improvements in object manipulation and completion of ADLs with the glove, after performing one warm-up trial with the glove. Overall, in the second glove trial, the median completion rate (effectiveness) in the JHFT across the eleven participants improved by 49.6% from baseline, meaning that participants could perform approximately 50% more tasks with the glove assistance in their second attempt.

Amongst all participants, the ones that received greater benefits from the glove were the most severely affected by SCI, with motor function corresponding to either a C5 or C6 motor level assessed with the ISNCSCI. Across the eight participants with lower baseline function, the average improvement in completion rate in the JHFT was 25% for the second glove trial (G2), compared to baseline. For individuals with tetraplegia unable to independently perform most ADLs, being able to complete an additional 25% of tasks could provide tangible benefits to their lives.

To assess their experience with the glove, all participants completed a usability assessment and, overall, expressed satisfaction with the glove, found the glove to be comfortable, and reported wanting to use this glove inside or outside their home. Due to some complexity with the testing set up, including a wrist wrap for the glove tubing and use of IMUs, we assisted all participants in donning the glove and accessories. On average, glove donning and doffing required 5 min and 1 min, respectively. We are continuing to iterate this glove design to allow for improved ROM and effectiveness of the actuators, speedier donning either by one's self or a caregiver, while still attempting to simplify construction of the glove itself to allow for the possibility of manufacturing. Our goal in the future is that glove complexity will decrease to allow for self-donning or simplified donning by a caregiver.



Across the three JHFT trials performed, the mean completion time (efficiency) did not change significantly, meaning that baseline performance speed was not significantly changed by the glove assistance. On average, in the second glove trial, participants were just  $0.7 \pm 13.4$  s slower than baseline, but faster than in the glove warm-up trial by  $5.1 \pm 8.1$  s. Considering that most participants already experienced great challenges with grasping and being effective on the JHFT, speed of performance was not expected to noticeably improve in the limited time participants had to adapt to the glove. In future research, more structured and lengthy training could be provided to participants in order to assess their adaptation to the glove over time and over repeated trials. Compared to healthy adults, individuals with SCI tend to be slow with all functional tasks. For this reason, we emphasized performance-based changes on the motor portion of the JHFT (i.e. success of attempts at moving cans, picking up objects) instead of the speed of task completion, which is how the test is designed.

Successful object manipulation with the glove was observed along with significant improvements in hand function for active range of motion of the fingers and maximum grasp strength. With the powered glove, the maximum grasp force increased by an average of  $9.5 \pm 4.6$  N for power grasp, and by  $2.7 \pm 4.5$  N for pinch grasp. The median grasp forces obtained with the glove of 11.7 N (power) and 5.5 N (pinch) are comparable with forces from other devices and are enough for holding most common objects encountered in daily life. As seen in the JHFT, lifting heavy and light cans were two of the tasks in which the glove most effectively and efficiently assisted hand function, which supports the glove's capacity to improve hand strength and assist in gross motor tasks. We believe this change in force production is sufficient for improvements in ADLs by the specified population due to the presence of proximal arm and torso weakness requiring that they only lift relatively light objects. Even with a glove that could theoretically provide higher grip forces, the user may not be able to lift heavier objects off the table surface.

For the simulated feeding task in the JHFT, a smaller improvement in performance was observed across participants. This could be explained by the retained capacity to perform the task with glove for most participants, and the difficulties in feeding experienced by the remaining due to their impaired shoulder function. That is, even though the glove provided enough grasp stability to hold the spoon, they were unable to lift the arm to place the beans inside the can. Given the ongoing limitations originating from shoulder dysfunction despite hand function was restored, future research should focus on developing a glove-shoulder combined system that could also provide proximal arm assistance to improve the whole arm synergistic functionality.

Regarding active range of motion, the maximum flexion of the MCP joints and maximum extension of the index PIP joint improved significantly with the glove. Whereas the maximum flexion values for the MCP joints with glove were greater than the minimum values needed for ADLs, the index PIP was approximately  $30^\circ$  less flexed than necessary. In extension, due to the glove's design feature to prevent overstretching of the

tendons, all joints were slightly more flexed than what would be desired for ADLs. Ideally, the glove should allow further extension of all joints by at least  $10^\circ$ , in order to increase the grasping aperture and facilitate grasping of larger objects, more closely resembling the ROM of an unimpaired hand.

Besides hand extension and strength, the shape of the hand during grasping is equally important for an effective dexterity, especially in tasks that require higher precision. For instance, for picking up coins and paper clips, a different type of grasp such as a tip pinch (only flexion of thumb and index) could have been set for the glove, instead of using the same tripod pinch as in writing. This aspect, together with the fact that small items were often visually obscured by the glove when placed on a tabletop, may have contributed to the lower performance observed in the task of picking up small objects. To optimize grasping with the glove, the effects of passive components on thumb ROM should be further explored, the glove's controller should be customized for the participants and specific object shapes and sizes, and a motion capture system could be used instead of a goniometer to collect and analyze ROM data with greater accuracy.

Overall, the button controller was an effective method, but posed challenges for our two distinct groups of participants: higher-functioning and lower-functioning. For the higher-functioning participants, we found that use of the button controller slightly slowed performance of tasks they could already perform at baseline due to waiting on the glove to inflate/deflate or inaccuracy with button-tapping. For the lower-functioning participants, use of a button controller demanded that they engage both limbs simultaneously to hold an object with one hand and press a button with the other, challenging for persons with such pronounced impairments. Since the glove is designed to be "transparent" when unpowered, it could be potentially used in the passive condition without restricting range of motion. This way, by selectively activating the glove for the tasks that require assistance and keeping it passive for the remainder, the participants could have received greater benefits from the glove during ADLs. Yet, compared to a physical button, the integrated soft sensors in the glove could potentially be utilized for a controller that could enable a more intuitive grasping, something important for individuals with severe dysfunction in both upper limbs. While future work should head in this direction, improved object manipulation was still demonstrated with the glove using a simple control strategy.

The main outcomes of this study are difficult to compare with existing results in the literature due to our focus on effectiveness over efficiency. The few studies found on ADL assistance in SCI used different hand function tests to evaluate the devices, namely the TRI-HFT [28], [45], [46]. In this study, the JHFT was chosen because, in contrast to the TRI-HFT, it is a widely used test in clinical practice and replicates ADLs with a higher, more realistic degree of complexity [34], [47], [48]. For instance, the ADL portion of the TRI-HFT only assesses gross motor function and involves maintaining a stable grasp of items for a few seconds and releasing them. This test does not specify how the object is to be picked up, but rather can be placed in the subject's hand by the researcher, as was

done in [28]. The JHFT includes fine motor tasks, repeated grasp/release of objects and reaching across midline. The JHFT was selected for this study, as opposed to continuing study from this lab using the TRI-HFT, to highlight the functionality of this new version of our glove in being able to manipulate small objects, such as picking up checkers off the table surface or even the paper clips and pennies that are part of this test. To this end, the JHFT can be perceived as more difficult and represents completion of activities of daily living more accurately. While our glove's range of motion could be further increased to facilitate improved dexterity with smaller objects, we demonstrated overall improvements in object manipulation for all other fine and gross motor tasks.

## VI. CONCLUSION

This study has demonstrated the effectiveness of a fabric-based soft robotic glove to improve independent performance of ADLs in individuals with hand paralysis resulting from SCI. Using the JHFT, we saw significant improvements in completion rate in the second glove trial across 11 participants with SCI and varying motor deficits. Participants with more severe impairments seemed to benefit the most from glove assistance. Range of motion in the fingers improved significantly from baseline with the glove powered. Powered glove grasp strength increased significantly by 9.5 N and pinch strength by 2.7 N over baseline. We plan to increase the portability of our glove system to allow for translation of these measurable improvements in range of motion and grasp strength toward increased success with real life skills in the user's natural environment. Future work should focus on customizing controls for determined tasks and user preferences, optimizing the glove's ROM, investigating the effects of prolonged training on adaptation to glove assistance and, lastly, exploring possible benefits of the glove in other populations such as stroke or muscular dystrophy.

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