Soft Robotic Glove with Integrated Sensing for Intuitive Grasping Assistance Post Spinal Cord Injury

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Abstract— **This paper presents a fully-integrated soft robotic glove with multi-articular textile actuators, custom soft sensors, and an intuitive state machine intent detection controller. We demonstrate that the pressurized actuators can generate motion and force comparable to natural human fingers through bench-top testing. We apply textile-elastomer capacitive sensors to the glove to track finger flexion via strain and detect contact with objects via force. Intuitive user control is achieved via a state machine controller based on signals from the integrated sensors to detect relative changes in hand-object interactions. Results from an initial evaluation with 3 participants with spinal cord injury (SCI), of varied injury levels and years since injury, wearing and controlling the glove show an average of 87% improvement in grasping force, and improvements in functional assessments for participants with recent injuries. A significant variation in response suggests further investigation is required to understand the adaptation needed across different injury levels and durations since injury. Additionally, we evaluate the controller and find an average of 3 seconds from user initiations to completed grasps, and 10% inadvertent grasp triggers and no false releases when objects are held.**

I. INTRODUCTION

Injury to the upper spinal cord can result in paralysis and impaired hand motor functions. Loss of hand motor functions is especially devastating as patients cannot independently perform activities of daily living (ADLs). Full finger range of motion, strength and dexterity cannot be restored post-SCI, leading to a need for take-home assistive devices.

In recent years, we have seen exciting growth in the field of wearable robotics for assisting individuals with physical disabilities. Some are aimed at assisting gait [1], [2], while others provide support to upper extremities [3], [4]. One popular design approach is using soft materials, such as pneumatic bladders or cable systems with compliant body anchors, to generate forces and torques to targeted joints. Although traditional rigid devices allow precise force and position tracking [5], soft devices do not require precise alignment with biological joints and embody ideal device requirements for home use such as comfort, compliance and low weight.

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Previous work in soft wearable robots for the hand involve assisting grasping and object manipulation [6]–[11]. Existing soft actuation methods have supported active finger flexion and extension through fluid-filled elastomeric chambers [9]–[12], cable driven systems with rigid or hybrid anchoring components [8], [13]–[15], shape memory alloy artificial tendons [16] or fabric-based bidirectional inflatable actuators [7], [17]. The effectiveness of some devices has been evaluated in human subject testing on SCI and post-stroke patients, demonstrating improvements in hand manipulation tasks and grip strength [18], [19].

While the majority of focus to date for these soft robotic devices has been in the area of hardware, there has been preliminary work in the area of controls to enable intuitive operation of the devices. Promising controls demonstrations include low-level actuator force and trajectory following [12], exercise-based mode selection [7], [20], and high-level user intent detection [7], [21], [22]. These studies have shown exciting proof of concept, but accurate, intuitive and robust control for soft wearable robots remains a challenge. Surface electromyography (sEMG) has been widely used in the control of advanced prosthetic limbs [23], [24], and it appears promising for providing intent detection in soft robotic gloves [21], [25]. However, sEMG can be challenging in certain patient populations due to its sensitivity to placement and dependency on distinct muscle activation. Various strategies, such as proportional EMG-envelope control [26] and support vector machine EMG classifier [27], have been aimed to overcome these challenges. While ongoing research of the aforementioned control techniques hold promise, there is also an opportunity to explore simpler solutions in the short term to aid device translation.

In this paper, we present the next generation of our textile-based soft robotic glove [17] that uses recent advances in textile-based capacitance soft sensors [28], [29]. The new glove is a single wearable garment with multi-articular textile actuators and custom sensors. Intuitive user control is achieved via a state machine based on signals from the integrated sensors detecting relative changes in hand-object interaction. In addition to design improvements, we also performed an initial validation with individuals with SCI.

II. GLOVE DESIGN AND INTEGRATION

A. Actuation

Compared to our previous textile glove with constant curvature bending actuators, this glove incorporates multi-articular actuators with gathered textile sections at the finger joints. The gathered sections provide increased localized material expansion to match natural finger motion. Each actuator is composed of two thermoplastic elastomer (TPE) chambers placed between three textile layers with different mechanical properties (Fig.1). The flexion air chamber is placed between the gathered layer and the inextensible layer, and its inflation results in articulated bending of the actuator. The extension air chamber is between two inextensible layers, causing actuator straightening when inflated.

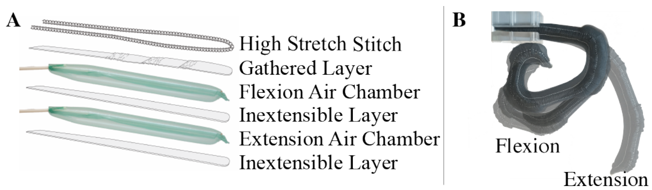

Fig. 1. Actuator design and actuation principle with (A) layered diagram of gathered pneumatic textile actuator, and (B) overlaid images of an actuator at flexion and extension.

B. Sensing

Capacitance textile strain and force sensors are attached to the dorsal side of the glove (which elongates during actuator flexion) and at the fingertips (to detect interaction forces during grasping) respectively. The sensor mats were constructed from two textile electrode layers joined with a dielectric elastomer layer, following methods used in [28].

To ensure detectable capacitance change for expected loading conditions and to specify electronic needs, sample sensors, laser cut from the fabricated sensor mats, were characterized for strain and normal force using an Instron Universal Testing Machine with loads estimated from use scenarios of the glove. For force characterization, three trials of five ramp cycles up to 25 N were performed. For strain characterization, three trials of five extension cycles up to 25% strain were performed. Fig.2 shows the characterization results and the images of the sensors used in the glove.

C. Passive Component

A passive thumb strap was designed to facilitate thumb motion during grasping, and can be used after a one-time fitting by a clinician. The thumb strap is anchored close to the first metacarpal bone and can be pulled across to the fifth metacarpal bone, bringing the thumb out of palmar plane and enabling thumb opposition.

D. Glove Integration

All sensors, actuators and passive component were integrated into a custom knit glove (Fig.3). The actuators were attached to the glove through the use of another high-stretch fabric layer connecting actuator seams to back of finger pockets. All sensors were integrated into the glove through first adhering to a sacrificial fabric and then sewing the sacrificial fabric to glove. In addition to the force and strain sensors for each finger, the palm force sensor was placed

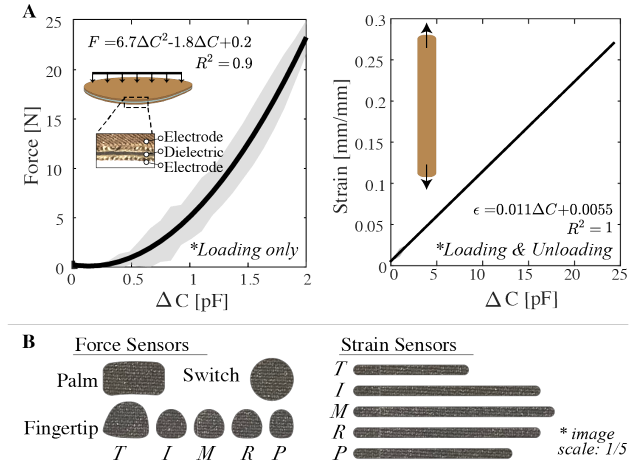

Fig. 2. (A) Soft sensor force and strain characterization results using sample sensors with geometry and size for index finger strain and force. The shaded areas denote the standard deviations. Illustrations and cross-sectional view of the sensor are also shown. (B) shows the sensors, at $1/5$ scale, used in this glove with their names, shapes and corresponding fingers, thumb (T), index (I), middle (M), ring (R), and pinky (P) if applicable.

between index and middle metacarpophalangeal joints and the switch force sensor was placed on a textile Velcro wrap and can be adjusted to anywhere around the wrist based on user preference.

Fig. 3. Integrated glove with highlighted sensors and passive component with illustrations of integration details.

III. Glove Characterization

We performed bench-top characterizations of the glove to understand its range of motion and flexion force.

A. Range of Motion

The range of motion of a single index finger actuator at each joint (gathered section) was measured and compared to the functional need of finger digits. The experimental setup and the joint angles measured are illustrated in Fig.4(A). A single actuator was placed parallel to a table surface underneath a fixed video camera. Using reflective markers at the actuator base, metacarpophalangeal joint (MCP), proximal interphalangeal joint (PIP) and distal interphalangeal joint (DIP), marker positions were obtained using MATLAB's

Image Processing Toolbox and used to calculate the joint angles. Specifically, the camera recorded the motion of the actuator as the flexion chamber pressure ramped from 0 to 25 psi and the extension chamber pressure ramped down from 25 to 0 psi at 2 psi/sec.

The maximum flexion angles of MCP, PIP and DIP were found to be of 106°, 105° and 123° respectively. The findings exceed the finger joint flexion needs for daily living of 80° for MCP, 104° for PIP and 68° for DIP [30]. Fig.4(C) also shows that the actuator exhibited consistent bending behavior at the higher (>20 psi) and lower pressures (< 10 psi), but was more variable in behavior in the mid pressure range possibly due to the randomness in gathered textile unfolding. When the glove is worn, the actuator pressures are toggled between 0 and 25 psi, and their performance is not affected by the high variability in mid-range pressure in application.

B. Glove Flexion Force

We evaluated glove flexion force as the force required to extend the four finger actuators with pressurized flexion chambers. The experimental set-up used an Instron Universal Testing machine as illustrated in Fig.4(B). The glove was donned on a tight-fitting finger-less mannequin hand and anchored with a fabric wrap around the mannequin's tapered wrist. The glove and mannequin were mounted under the Instron loadcell which was attached to a horizontal grip bar. The pressurized actuators wrapped around the grip bar imitating flexed fingers pulling down. At each constant flexion pressure condition, the grip bar was lifted at 0.5 mm/s until a total displacement of 40 mm.

At maximum flexion pressure and grip bar displacement, a total force of 37 N, or approximately 9.3 N per finger actuator was measured. This force level is comparable to previously quantified grasping forces during ADLs [31]. At 0 flexion pressure, a maximum of 1.2 N was detected, indicating a small amount of frictional load in this set-up.

IV. Control System

To achieve an intuitive control system for the glove, we developed a state machine controller that leverages relative changes in soft sensor signals from hand-object interactions.

A. Hardware Research Platform

The glove is powered by a custom-built fluidic research platform (Fig.5), as opposed to a miniature actuation box designed for product translation, to allow rapid prototyping of controllers and flexibility in testing conditions. The air source for the control platform is a portable compressed air bottle capable of storing up to 1.9 L of at 4500 psi. The air source is regulated through one global mechanical regulator and one electronic pressure regulator (SMC electro-pneumatic regulator) in series. The regulated air is split into 16 channels, each with its own flow sensor (Omron D6F Series) and pressure sensor (Honeywell Board Mount Pressure Sensors), and bidirectional valves. The pneumatic control box uses SpeedGoat's mobile target machine programmed using Simulink Realtime for data acquisition and real-time control. The soft sensors are read with Analog Microelectronics CAV444 capacitance to voltage converter in series with SpeedGoat IO 322 board, together allowing sufficient (femtofarad) sensor resolution.

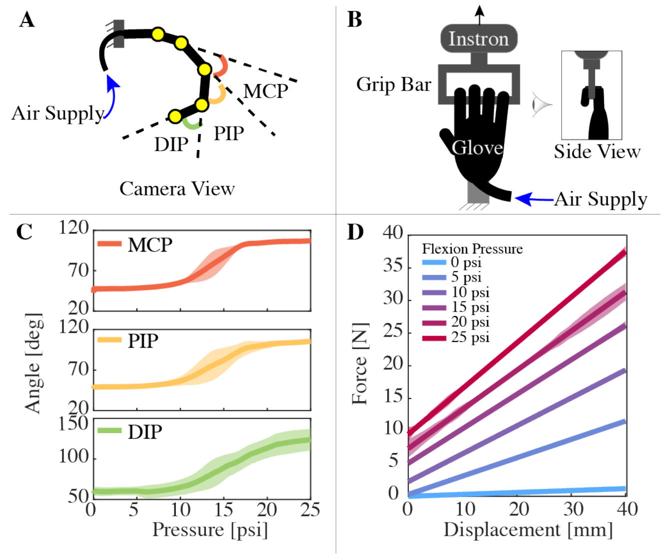

Fig. 4. (A) and (B) illustrate the testing set-ups for range of motion and flexion force characterization experiments, and (C) and (D) are the results of the respective tests. The shaded areas denote the standard deviation.

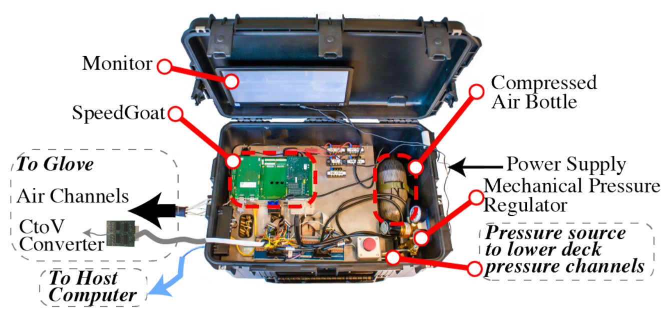

Fig. 5. Image of pneumatic control box with labeled components. Items exiting the control box include: grouped air channel lines and CtoV converter to the glove, ethernet connection to host computer, and mechanically regulated air sent to lower deck pressure channels.

B. Controller Details

We focused on a simple and effective control strategy to enable power and pinch grasps, which are essential for ADLs. The controller includes four states: relax, extension, pinch flexion and power flexion. Although the choice of four states would not be suitable for dynamic grasping, for those with hand impairments, even modest improvements to power and pinch grasps can be meaningful. The four state controller enables us to quantify these improvements with human subject experiments described later in this paper.

The transitions among all states are determined using thresholding techniques with soft sensor signals. The palm sensor, thumb, index and middle force sensors and switch force sensor are used in determining state transitions. Data from other sensors were collected during preliminary testing to use for future development. Baseline sensor signals, B, are first captured when the glove is donned. The threshold parameters, δ, are the deviation of V, current sensor readings, from baseline signals required to trigger a state transition. Nominal threshold parameters were chosen during iterative design and some parameters required further tuning or individualization to account for variations in glove fit, and residual finger strength for each user. In the future, this limitation of parameter tuning can be eliminated by mapping out threshold sensitivity as a function of hand size and tone using more participant data.

Fig.6 (A) illustrates the details in transition criteria. From a relaxed state, crossing the threshold of either palm force sensor, $V_{palm} > B_{palm} + \delta_{palm}$ or fingertip force sensors, $V_{fingers} > B_{fingers} + \delta_{fingers}$ will lead the glove to the extension state. From the extension state, the glove can either transition into pinch flexion or power flexion depending whether the palm sensor or fingertip sensors cross their respective thresholds first. From either flexion or extension, the glove can be released by the users by contacting the switch sensor using other body parts or objects such as edge of the table or wheelchair armrest.

For each state transition, the corresponding air channels that require increases in pressure follow a 20 psi/sec reference pressure ramp using a flow PID controller, and the air channels that require a drop in pressure exhaust air directly through the exit valves.

Due to repeatedly loading the sensors in force and strain, the elastomeric dielectric layers do not recover to original thickness instantaneously, resulting in sensor baselines increasing over time. In practice, reading relative capacitance changes is sufficient for detecting hand-object interaction by comparing sensor loading between current and previous time steps. To capture these relative signal changes, dynamic baselines of palm and fingertip sensor signals were used. Specifically, $B_{palm}, B_{fingers}$, take on the maximum between the current baseline and the running means.

V. Evaluation

To understand the performance and impact of the integrated glove and state machine controller, we performed a preliminary evaluation with SCI participants with different injury levels and years since injury.

A. Methods

Under a Harvard University IRB-approved protocol, 3 participants, with SCI ASIA levels of C4-C5 [32], were recruited for the study. The participants (P1-P3) were male with average age of 58.7. We selected participants with variations in years since injury and injury level; S1 had an old injury of 39 years and relatively higher injury level of C4, S2 had a recent injury of 1 year and the same higher injury level C4, and S3 had a recent injury of 4 years and a lower injury level of C5.

The first evaluation involved comparing grasp force without and with wearing the glove. We measured participants' grasp force in the baseline condition without wearing the

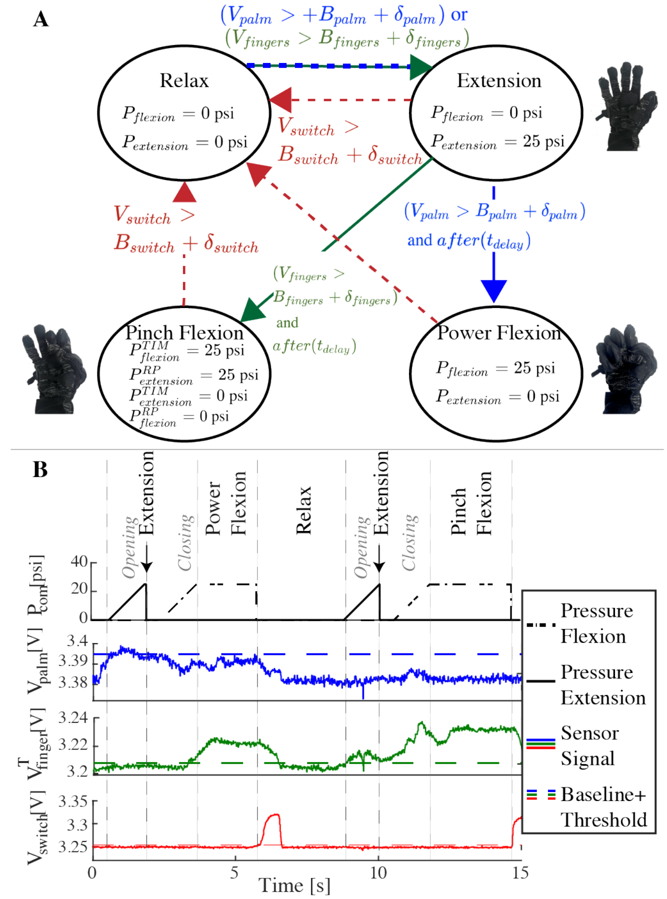

Fig. 6. (A) Controller state machine showing the four states and transition criteria. For each state, the actuator chamber pressures are shown, with subscripts indicating flexion or extension and superscripts indicating the corresponding finger (TIM = Thumb, Index, Middle) (RP = Ring, Pinky). (B) An example of controller operation showing the corresponding command pressure, sensor signals, and sum of sensor baseline and thresholds.

glove (BL), and in the active condition with wearing the powered glove (G). Participants grasped a cylinder wrapped with (Tekscan) pressure mat, and the peak force were recorded over three trials in each condition.

Additionally, two standardized hand function tests, Jebsen Hand Function Test (JHFT) and Box and Blocks Test (BBT), were conducted. Both our own observations and past work [33] suggest assistive devices require human adaptation time to maximize the potential benefits users can receive. Thus, with possible human adaptation effects in mind, we allocated the limited testing time with our participants to one trial at baseline (BL) and three trials in active condition with participants wearing the glove (G1, G2, G3) for each hand function test. For JHFT, 5 of the 7 standard subtests (turning index cards, picking up and dropping small objects in a jar, stacking checkers, lifting light and heavy cans) that require repeated cycles of finger extension and flexion, were conducted. The participants had 2 minutes to complete each subtest of JHFT, and both the time used and the number of items moved were recorded with the score calculated as number of items successfully moved per minute. For BBT, participants were instructed to move as many blocks across a barrier as possible in 1 minute with the score being the total number of blocks moved. An occupational therapist conducted both hand function tests and trained the participant on using the glove up to 20 minutes prior to the start of the active condition trials with objects not used in JHFT or BBT.

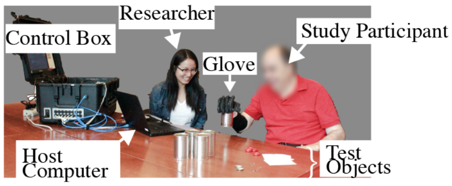

Fig. 7. Experiment set-up for glove evaluation on participants.

To quantify controller performance, we measured the time between the user initiation of a grasp and the time the glove transitions first to extension and then from extension to flexion. We also measured the percentages of false positive controller responses, defined as glove responding in ways unintended by the user. To collect data for the response time metric, the therapist timestamped the events of user initiation, glove extension, and glove flexion at 1 second intervals during active conditions. The user initiation event was determined by the therapist through observation of implicit motions like reaching for the object or direct expression of intent from participants. The number of false positive triggers, unintended glove state transitions from relax to extension or extension to flexion, and number of false positive releases, unintended glove transition from flexion or extension to relax, were counted and compared to the number of total grasping intents in all active trials.

B. Results

1) Grasp Force: All participants showed improvement in their grasp force measurement. As shown in Fig.8, across all participants, the average grasp force at baseline was 1.6 N and the average grasp force in active condition when wearing the glove was 3 N, an increase of 87%. Understandably, the force improvements are lower than the glove flexion force measured during bench-top characterization, as the two experiments introduce different external loads to the actuator. Specifically, during bench-top characterization, the actuator is fixed at its base and loaded with a small contact area at one of its bending segments, and the Instron measures all downward forces including a mix of friction and the actuator textile's inherent elasticity. In the human subject experiments, the glove is worn on the hand and the actuators transmit the force along the entire finger and are resisted with finger joint stiffness, commonly high in individuals with SCI due to contracture and spasticity [34] [35].

2) Hand Function Tests: Fig.9 presents hand function test results among participants in all test conditions.

P1, a participant with a decades-old and high level injury, did not improve in the JHFT and BBT in the active condition compared to baseline. Although wearing the glove did not improve P1′s overall hand function tests scores, there was

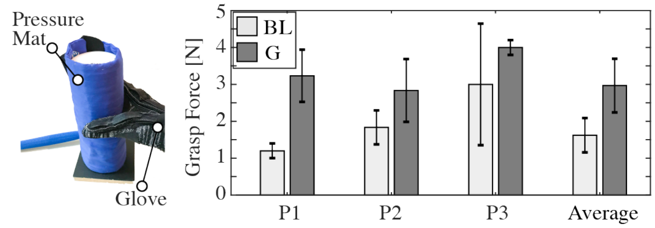

Fig. 8. Grasp force measurement method (left), and results (right) showing all participants improved in active condition (G) compared to baseline (BL).

improvement in particular tasks. Specially, P1 was unable to stack checkers in the baseline condition, but was able to stack checkers consistently in the active condition trials.

P2, a participant with a recent and high level injury, did improve in both JHFT and BBT scores when wearing the glove. P2 scored higher in the active condition as compared to baseline in four JHFT subtests and improved in BBT scores in all active condition trials. Specifically comparing the best active condition trial to baseline, P2 improved from moving 0.58 items/min to 1.48 items/min in JHFT, from 0 blocks to 4 blocks in BBT. Other interesting observations include the decline in P2's performance in the checkers test and the large improvement during G3 for light cans. The variability can be attributed to either device performance or wearer adaptation over time, and these observations motivates future studies to isolate the potential causes.

P3, a participant with a recent and lower level injury, had higher baseline scores than both P1 and P2, also improved in the hand function tests in active condition. P3 improved in all JHFT subtests and BBT, and generally showed performance gains over the course of the three trials, with some minor variability. Comparing the best active condition score to that of baseline, P3 improved from moving 3.84 items/min to 6.6 items/min in JHFT, from 7 to 9 blocks in BBT.

Although the hand function test results were highly variable, we saw that despite different injury levels, the two participants with recent injuries, P2 and P3, were both scored higher on the hand function tests using the glove. This observation suggests the current version of the glove may benefit a sub-population of SCI individuals with hand impairments. Among many possible reasons, we hypothesize P1's lack of improvement on the hand function tests may be due to receiving insufficient training time with the therapist. This hypothesis is evidenced by P1's use of all of the 20 minutes of allowed training time, while P2 and P3 completed training under 16 minutes. Further research is necessary to understand both the type of device assistance and control required for individuals with older injuries, as well as their exact learning and adaptation to device patterns.

3) Controller Performance: Fig.10 shows the controller average response times, and percentage of false positive trigger and releases grouped for each task of JHFT and BBT. The controller performance results show considerable differences among the different objects of manipulation. Across all tasks, the average time from user initiation to glove extension was 1.3 seconds and average time from glove extension to flexion

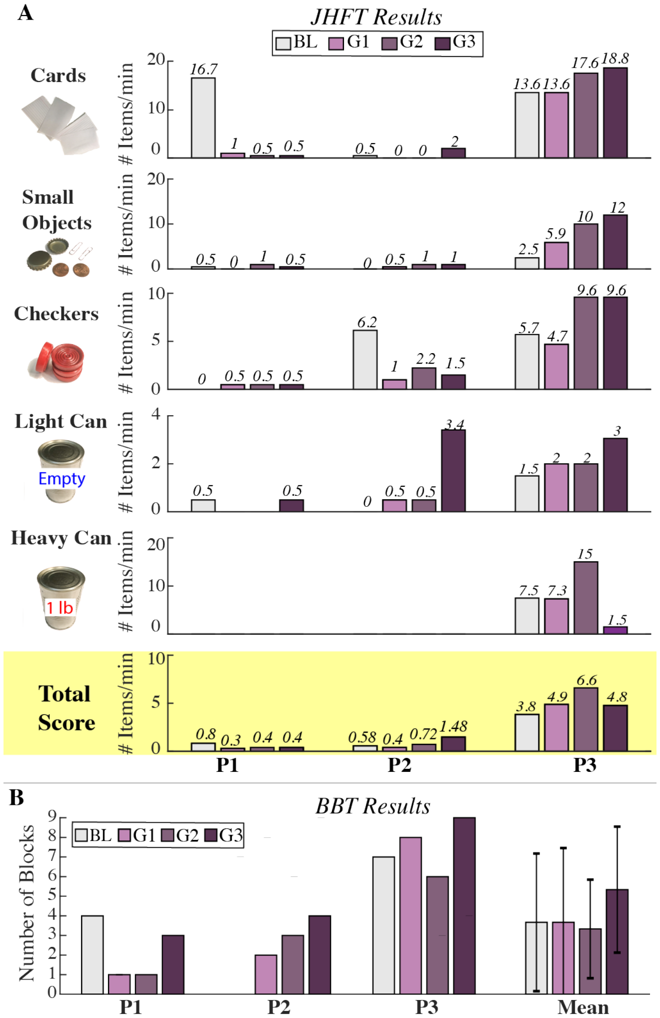

Fig. 9. (A) Jebsen Hand Function test (JHFT) results with performance of each participant (P1 - P3) on each subtest. Each column presents the data from one participant and each row is the result of a different JFHT subtest. (B) Box and Blocks test (BBT) results with scores from each participant during each trial.

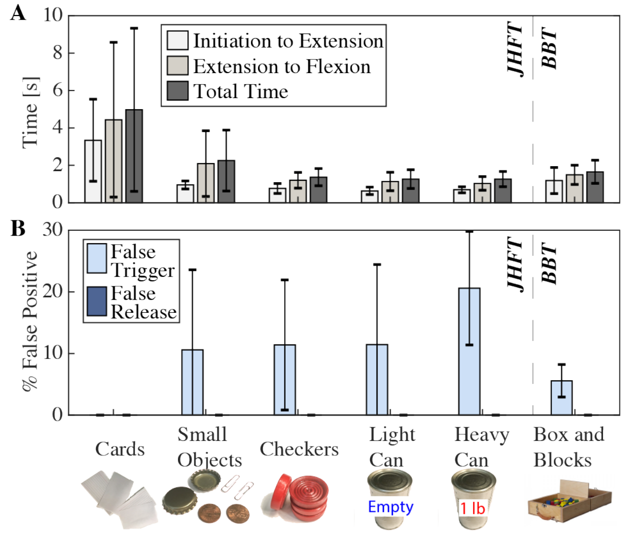

Fig. 10. Controller performance results for each task with (A) showing the average times between user initiation and glove state transitions and (B) showing the percent false positive triggers and releases.

was 1.9 seconds, giving an average total time between user initiation and glove flexed and grasping of 3.2 seconds. Card turning had the most delays and variability, possibly due to the lightweight nature of the index cards, making it difficult to detect contact with the soft sensors during attempted grasping. We found an average of 9.9% false positive triggers across all test trials with all participants. More importantly, no false positive glove releases were found. The heavy cans resulted in the highest percentage of false triggers; we hypothesize this can be explained by increased muscle tension after attempts to lift heavy objects, resulting in extra movements of hand within the glove causing false triggers. We also observed some spasticity experienced by participants during and after this subtest, potentially contributing to extra pressure applied to the soft sensors.

In addition to the quantitative results, we also collected qualitative information through an user survey. P2 and P3 both agreed or strongly agreed that the controller responded fast enough for their needs and that the controller triggered at the right times. P1 having not used the device successfully possibly due to insufficient training time, neither agreed or disagreed. The average delay times appear satisfactory when compared to the time delay endured by individuals with SCI who cannot pick up objects. Additionally, the zero false positive release percentage ensures the wearers will not unintentionally drop objects when wearing the glove, and a low false positive trigger percentage will not cause significant harm to the users.

VI. Conclusion

In summary, we demonstrated an upgraded soft robotic glove with soft sensing based state machine controller being independently operated by 3 SCI participants. Using standard hand function tests to evaluate device performance on human subjects, we saw variation in the results across the individuals, but all three subjects showed hand function score improvement in multiple metrics.

These preliminary results motivate further study to investigate the performance of the glove and the effects of human adaptation. Particularly, it would be interesting to formally study how training with the glove may improve the level of benefit the glove may or may not provide across a variety of different manipulation tasks. This work also helped us understand additional device requirements such as robust control strategies capable of distinguishing between user intent and spasms within the glove in order to reduce false positive rates and increase device reliability. Finally, we envision that improved function will be possible through enhancing the actuation platform and customization of assistance to different individuals through an optimization-based control approach.

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