EMG Controlled Soft Robotic Glove for Assistance During Activities of Daily Living

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***Abstract*—This paper presents further developments, characterization and initial evaluation of a recently developed assistive soft robotic glove for individuals with hand pathologies. The glove technology utilizes a combination of elastomeric and inextensible materials to create soft actuators that conform to the user's hand and can generate sufficient hand closing force to assist with activities of daily living. User intent (i.e. desire to close or open hand) is detected by monitoring gross muscle activation signals with surface electromyography electrodes mounted on the user's forearm. In particular, we present an open-loop sEMG logic that distinguishes muscle contractions and feeds the information to a low-level fluidic pressure controller that regulates pressure in pre-selected groups of the glove's actuators. Experiments are conducted to determine the level of assistance provided by the glove by monitoring muscle effort and mapping the pressure distribution during a simple grasping task when the glove is worn. Lastly, quantitative and qualitative results are presented using the sEMG-controlled glove on a healthy participant and on a patient with muscular dystrophy.**

Keywords*—*soft robotic glove; soft actuator; hand assistance; EMG; electromyography; activities of daily living;

I. INTRODUCTION

Hand function plays an important role in performing activities of daily living (ADL) and maintaining an independent and healthy quality of life. However, people afflicted by stroke, cerebral palsy, muscular dystrophy, or traumatic brain injury may lose the ability to actively and accurately control the wrist, thumb, and fingers. Untreated, these deformities contribute to the loss of advanced grasps [1], [2] and the ability to perform many fundamental activities of daily living.

Physical therapy has been shown to be beneficial for improving hand function in patients with acute conditions; however, current practice is labor intensive, costly, and limited to clinical environments [3], [4]. Individuals with degenerate conditions often suffer from deficits and require assistance to compensate for loss of muscle strength. Therefore, an assistive device that can provide grasp assistance for ADL, or task-specific training, could play a critical role in augmenting hand function over the course of their life.

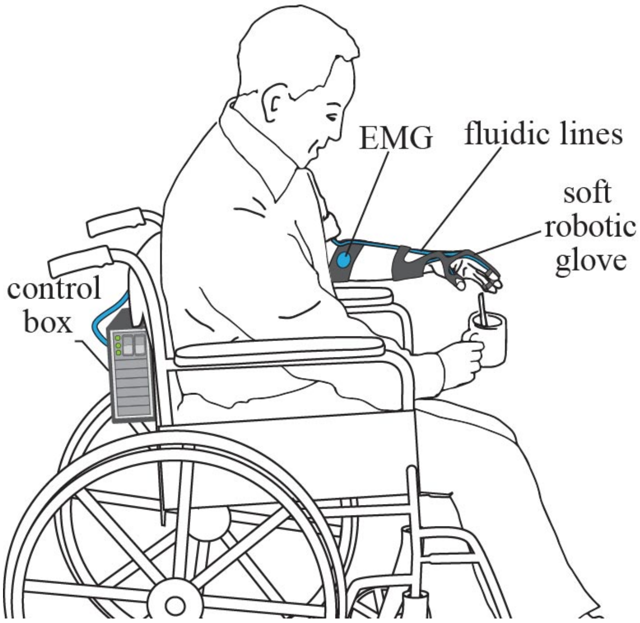

Figure. 1. The concept of providing assistance in activities of daily living to individuals with hand impairments through the use of a soft robotic glove that detects user intent through EMG signals in the forearm.

The majority of existing wearable robotic hand devices have been developed for rehabilitation purposes and consist of mostly of rigid exoskeleton designs that are often heavy and can be difficult to align with the biological joints of the hand [9], [10]. In addition, these devices are typically intended for use in a clinical setting and are often not well suited for use as an assistive device or task-specific training such as the Box-and-Block test, the Nine-Hole Peg test, or the Jebsen hand function test. Recently, new approaches have emerged with designs for assistive hand devices that utilize flexible and soft materials such as cable-driven or fluidic soft actuators for supporting finger motion [11]-[19]. These devices provide assistance to the wearer without rigid joints and links, which makes them more robust to misalignment, lightweight, and easier to don and doff. These developments are opening up new possibilities for how wearable robotics can be used in certain patient populations.

In this paper, we describe recent results related to the characterization and control of a soft robotic glove (as presented in [20]) for restoring basic hand use for individuals who have peripheral nervous system conditions, including hereditary muscle disorders (e.g. muscular dystrophy), nerve diseases, and Amyotrophic Lateral Sclerosis (ALS, Lou Gehrig's disease). The glove utilizes soft fluidic actuators, previously described in [20], that when pressurized can generate motion paths that are kinematically similar to the motion of the human finger and thumb, yet require only simple control inputs (i.e. pressurization). With respect to control, there are several human-robot interfaces for detecting user intent including mechanical solutions such as switches (toggle, sip/puff), auditory sensors that record voice commands, and sensors that detect biological signals (EEG, EMG). In section II, we explore a control scheme where surface electromyography (sEMG) sensors are mounted on the forearm to detect gross muscle activation signals responsible for hand flexion and extension. The user can preselect by means of mechanical switches the group of fingers that will activate based on the sEMG signals. This is one of the least invasive methods to detect user intent and has the potential to work across a range of acute and chronic hand pathologies to provide assistive benefit (see Figure 1 for concept illustration). Section III describes experiments where the electrical muscle activity of a healthy participant was measured while the glove was manually activated (i.e. without making use of muscle effort to control the glove). These experiments were done to demonstrate the potential of the soft robotic glove to generate forces adequate for grasping of objects when operated from users with no muscle strength. Further, the glove's total grasping force and the pressure distribution on an object are also presented. In section IV, we demonstrate the use of sEMG for sensing user intent and controlling the glove for performing task-specific exercises on a healthy subject and on a patient with muscular dystrophy.

II. THE ASSISTIVE SOFT ROBOTIC GLOVE

A. *Soft Robotic Glove Design*

In previous work [21], the authors describe the design, analysis, and characterization of fluidic soft bending actuators that are constructed using a combination of elastomeric and inextensible materials. In further developments, multi-segment fiber-reinforced silicone actuators were introduced and shown to enable complex behaviors in which more than one motion can be programmed in series along the length of a single actuator and achieved by means of simple fluidic pressurizations [20], [22]. A series of these multi-segment soft actuators were developed to support flexion and extension of the thumb and fingers, and integrated into a textile glove form factor [20]. It should be noted that selection of flexible/soft components is one of the distinctive features of the soft robotic glove architecture and results in a design that is simple, lightweight, easy to fabricate, customizable, and safe/comfortable to wear (i.e. no pinching or pressure points) [21].

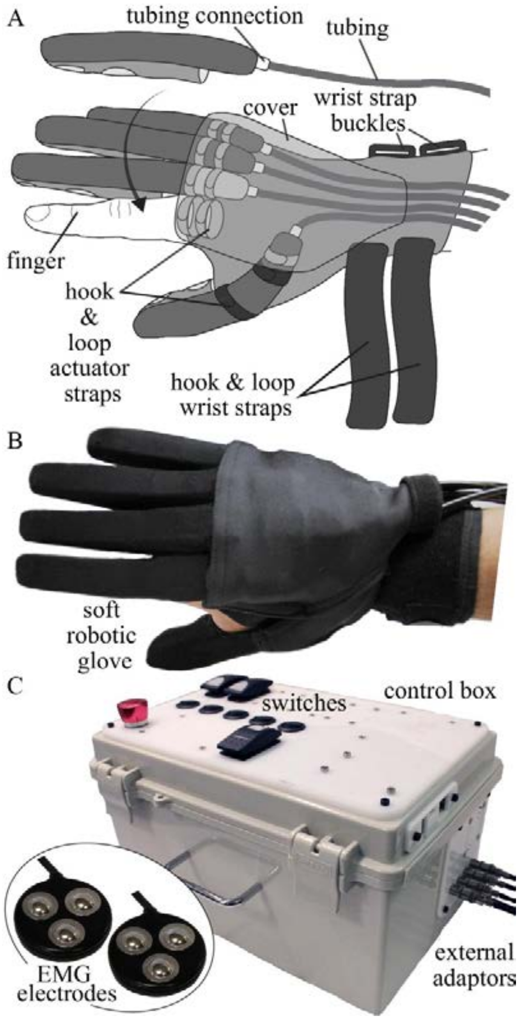

Figure. 2. A. Illustration of the textile layers showing the individual components of the soft robotic glove, B. the fabricated soft robotic glove prototype, and C. the control box with all the integrated electro-hydraulic components and sEMG electrode sensors.

The individual textile layers of the glove are illustrated in Figure 2A and their function is described in detail in [20]. Figure 2B and C show the complete soft robotic glove prototype and the dedicated control box respectively. The control box integrates all the necessary electro-hydraulic components [20], such as fluidic pump, valves, microcontroller, and two surface electromyography (sEMG) sensors (Myomo Inc., Boston, MA) to enable user intent recognition. Additionally, the external casing carries mechanical on/off switches that enable the user to manually pre-select only those actuators on the glove that are required to be activated for a specific task. Lastly, external adaptors at the side of the control box (see Figure 2C) allow for simple and quick connection with the fluidic lines of the glove's actuators.

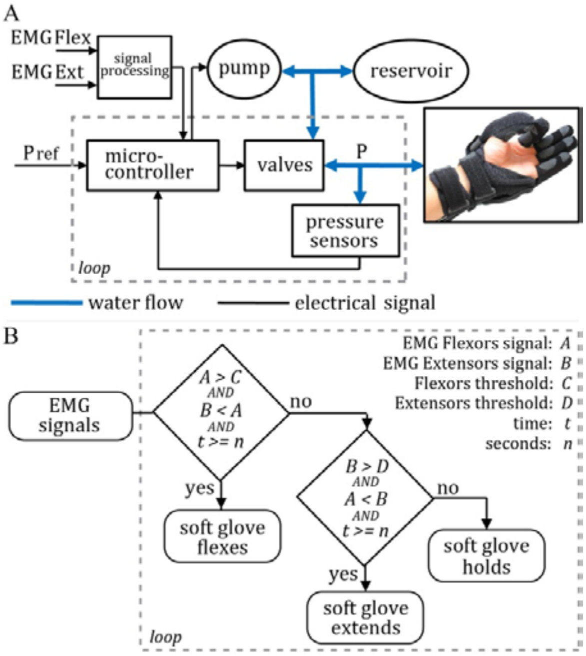

Figure. 3. A. The control scheme for the soft robotic glove. The processed sEMG signals are measured from FDS and EDC muscles and are sent to the microcontroller that regulates the pressurization level of the soft actuators. B. Flowchart of the EMG logic used to detect user intent. The state of the two sEMG signals is compared to three predefined conditions that result in the glove flexing, extending, or holding its form.

The implemented control scheme for the soft robotic glove is shown in Figure 3A, where sEMG signals are captured from two muscles on the forearm, amplified, filtered and quantified. The processed information from the signals is sent to a microcontroller where it progresses through a series of conditions (EMG logic) that are responsible for the activation and deactivation of a low-level controller. In turn, the low-level controller uses pulse width modulation (PWM) to command the opening and closing of the valves and pump based on pressure measurements within the fluidic lines of the actuators.

B. *Surface Electromyography (sEMG) Logic*

User intent of gross flexion and extension of the fingers and thumb can be detected by measuring the electrical activity of two muscles on the forearm using surface electromyography (sEMG) sensors. The first of the electrodes is placed at the Flexor Digitorum Superficialis (FDS) muscle to measure gross finger flexion, and the second at the Extensor Digitorum Communis (EDC) to measure gross finger extension. The electrical range of these two muscles is monitored and signal gains along with threshold parameters can be adjusted prior to use to enable the end user to simultaneously control a pre-selected group of actuators (see Section IIA) without having to provide maximal muscle contraction effort. For example, with the current research platform (control box), if the user needs to perform a tripod pinch grasp, the thumb, pointer and middle actuators would be preselected by turning those switches on such that when the user activates the glove these actuators will support these fingers leaving the other two unpressurized.

The open-loop sEMG logic hierarchy, of which an example is shown in the flowchart in Figure 3B, allows control of the soft robotic glove by continuously monitoring and comparing the state of the two muscle signals (FDS and EDC) to three predefined conditions: a) 'flex', b) 'extend', and c) 'hold'. The parameters of these conditions are set and adjusted based on initial assessments relating to the user's pathology and residual muscle activity. The 'flex' condition can be met when the processed signal from the FDS muscle crosses over a flexor threshold, for duration greater than a specified amount (time-over-threshold statement), while at the same time the EDC muscle signal has a value lower that the FDS signal. This condition pressurizes the fluidic soft actuators, thus flexing the glove along with the biological fingers. Similarly, to trigger the 'extend' condition that opens the biological fingers, the EDC muscle signal must cross over an extensor threshold, for duration greater than a specified amount, while at the same time the FDS muscle signal has a value lower that the EDC signal. While this

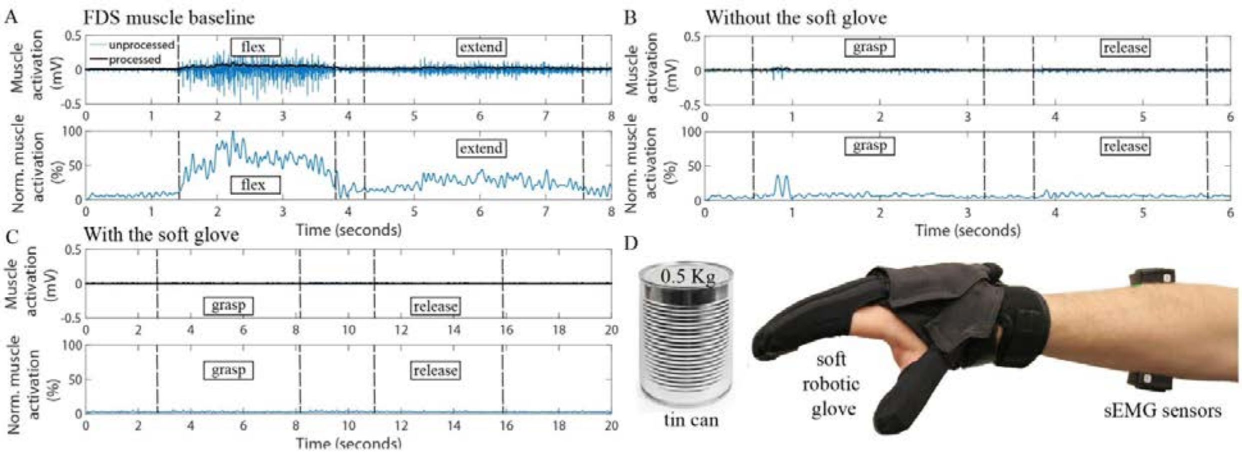

Figure. 4. The unprocessed, processed, and normalized muscle activation (EMG) signals for FDS: A. baseline test without assistance from the soft robotic glove, B. grasping and releasing of a tin can without assistance from the soft robotic glove, and C. grasping and releasing of a tin can with assistance from the soft robotic glove. D. the placement of the wireless Delsys sEMG sensors on the forearm.

condition is true, the actuators will be depressurized, allowing the elasticity of the elastomers and textiles that form the glove to passively return the biological fingers to the extended position. Finally, when both of the previously described conditions are not met, the 'hold' condition is activated and the glove can maintain the present fluidic pressure within the soft actuators. Any of the three glove states -- flex, extend and hold -- have the ability to remain active for as long as the corresponding condition of the sEMG logic hierarchy remains true. The time-over-threshold statement within the conditions ensure that involuntary muscle contractions will not be interpreted by the microcontroller as intended commands by the end user to flex or extend the hand.

III. EXPERIMENTAL EVALUATION

A. *Soft Robotic Glove and Grasping Muscle Effort*

An experiment with a healthy participant was conducted to examine the ability of the soft robotic glove to perform grasping, and generate sufficient force to prevent an object from being dropped without the need to provide biological muscle effort. For this experiment, two, double differential sEMG electrode sensors (Trigno Wireless System – Delsys, Boston, MA) were placed on top of the FDS and EDC muscles of the user's arm to record only the muscle activity (i.e. not to control the soft robotic glove) in three sub-experiments. The first was a baseline test, where the user was instructed to perform maximal voluntary muscle contractions (VMC) while flexing and extending the fingers of the hand. With this test, the maximum muscle effort values were obtained. The second sub-experiment required the user to perform an isometric muscle contraction to grasp, lift and hold, and then put down and release a 75 mm diameter tin can with a weight of 500 grams. For the last sub-experiment, the user was asked to wear the soft robotic glove and repeat the latter sub-experiment without providing any physical muscle effort and by allowing the glove to perform the grasping motion. In all experiments, the sEMG sensor location on the forearm remained unchanged so that readings could be easily compared across trials.

Due to the inherent variability of EMG signals, during post-processing the collected raw signals were full-wave rectified, filtered with a 4th order low-pass Butterworth filter with cut-off frequency of 10 Hz, and normalized against the baseline VMC. This process is the suggested one by the international society of electrophysiology and kinesiology (ISEK) guidelines that enables physiological interpretation of EMG data [23]. For all sub-experiments electrical muscle data were collected with a sampling rate of 2000Hz. In Figure 4A-top the unprocessed and processed muscle activation signals of FDS muscle for the baseline test are shown along with the normalized muscle effort (Figure 4A-lower). Figure 4B and C show the sEMG signals from the tin can grasping experiment with and without assistance from the soft robotic glove respectively. The normalized muscle effort for grasping the tin can unassisted was measured to be 12.7% of the VMC. In contrast, the normalized muscle effort with glove assistance was found to be close to zero and within the noise levels of the EMG sensor. This experiment demonstrated that there was minimal, to no biological muscle effort involved in grasping the 500 gram tin can. Similarly, the EDC muscle results demonstrated reduction in muscle effort when the glove was worn by the user.

B. *Pressure Distribution Maps*

To characterize the contact forces applied by the soft robotic glove when worn, the experimental setup shown in figure 5A was utilized. The setup consists of an acrylic cylindrical tube with a diameter of 100 mm that is wrapped with an ultra-thin and calibrated pressure sensitive sensor film (Tekscan 5250, Tekscan Inc., Boston, MA). The glove was worn by a healthy participant and pressurized to the desired level. During the experiment the glove was manually activated and the individual wearing the glove was asked to relax all hand muscles to eliminate the contribution of their biological hand strength on the data collected.

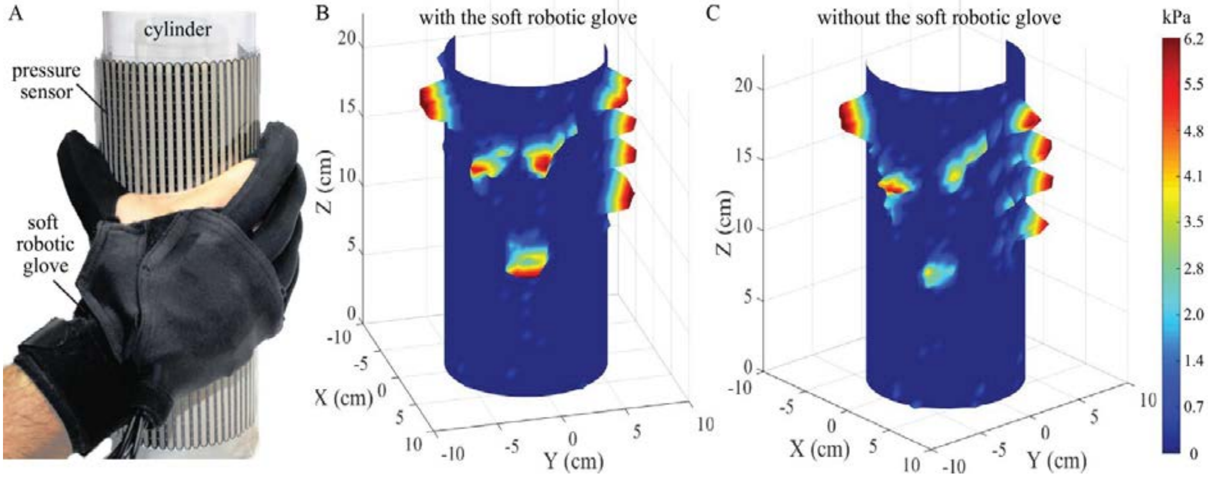

Figure. 5. A. Setup for obtaining contact pressure distribution, B. Pressure distribution on cylinder when all actuators of the soft robotic glove are pressurized, and C. Pressure distribution while the individual grasps the cylinder using his hand without the soft robotic glove.

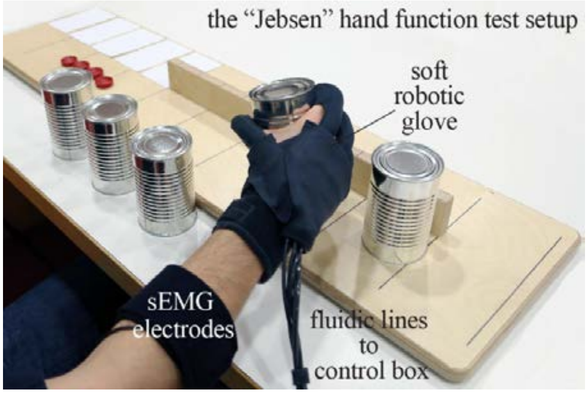

Figure. 6. User performing the standardize Jebsen hand function test wearing the robotic glove that is controlled through sEMG signals read from the fingers flexor and extensor muscles on the forearm.

Figure 5B, shows the pressure distribution obtained when all soft actuators of the glove are pressurized to 413 kPa, and the user is not contributing to the grasp with their physical strength. The total contact force generated by the glove was obtained by integrating the volume under the pressure distribution surface and was found to be 14.15 N for the depicted trial. In comparison, figure 5C presents the pressure distribution map when the participant grasped the cylinder without the glove (i.e. using their physical grasp strength), at a similar amount of total contact force. The total force exerted by the hand on the cylinder was 14.38 N. Assuming a coefficient of static friction of 0.5, the results indicate the grip force generated by the glove is sufficient to grasp objects of around 700 grams which agrees well with the results from our sEMG experiments. In addition, the data from the maps show that the pressure distribution obtained using the soft robotic glove is qualitatively similar to the distribution obtained using a functional hand.

IV. PRELIMINARY USER STUDIES

The soft robotic glove with EMG controls was evaluated in a preliminary user study with a healthy participant and a patient with muscular dystrophy. For the participant studies, two sEMG sensors (Myomo Inc., Boston, MA) were mounted on the forearm on the FDS and EDC muscle groups for each participant. The study was approved by the Harvard Medical School Institutional Review Board.

A. *Healthy Participant*

The system was first evaluated on a healthy subject to ensure the control logic operated robustly during typical activities. Following the EMG logic discussed in Section IIB, the user was able to control the state of the glove with only the activation signals from the two muscle groups. The participant was tasked with completing several of the subtests in the Jebsen hand function test (Figure 6) namely, lifting five large, light objects (50 g soup can), lifting five large, heavy objects (500 g soup can), stacking four 1-1/4" diameter checkers, and simulated page turning of five 3"x5" index cards [24]. The participant was able to complete the tasks in 29, 39, 26, and 44 seconds, respectively. These times are approximately an order of magnitude slower than reported normative data for healthy individuals with no assistance; however, for individuals with a hand impairment, the added support from the soft robotic glove could make the difference between completing the task or not. Similar studies will be performed on impaired individuals in the future.

B. *Hand impaired Participant*

A preliminary evaluation of the system was performed on a participant with muscular dystrophy. The participant demonstrated some proximal arm strength (i.e. able to lift arms), but had extremely weak hand strength with little to no spasticity or contractures. In a preliminary evaluation of their sEMG signal strength, both FDS and EDC muscles were found to be sufficient (i.e. large enough amplitude) for the user to operate the soft robotic glove with the sEMG control logic described in section IIB. Figure 7A, shows still photographs of the three glove states that include: grasping, holding, and releasing a wooden block using the soft robotic glove with sEMG control. Figure 7B shows data collected of the two sEMG signals alongside their corresponding thresholds. The three glove conditions, as previously described in section IIB, are shown in the same graph for the three different signal states: flex, hold, and extend.

V. CONCUSIONS

In this paper, we presented recent advancements of a soft robotic glove that can assist individuals with functional grasp pathologies in performing activities of daily living. Thanks to the inherent compliance and simplicity of the soft

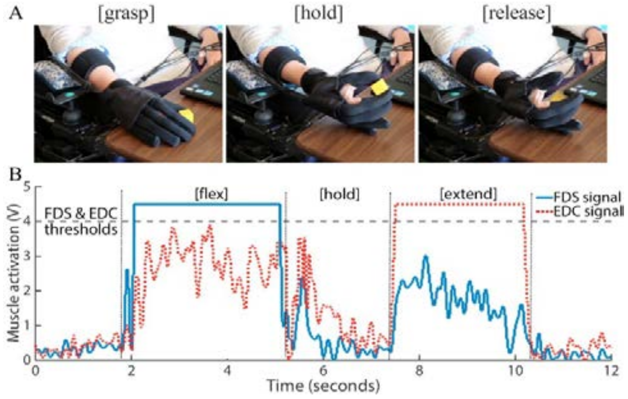

Figure. 7. A. Video stills showing the hand impaired participant grasping, holding, and releasing a wooden cube with the aid of the soft robotic glove and the sEMG control logic. B. Collected data showing the conditioned sEMG signals and their thresholds. The graph shows how the flexor muscle triggers pressurization of the glove to assist with grasping when the flexor signal (FDS) is above the threshold, while at the same time the extensor muscle signal is smaller than the flexor muscle signal. (left). The middle part, represent the holding condition where both muscle signals are below their thresholds. The last part (right) shows how the extensor muscle triggers depressurization of the glove to assist with extending when the extensor signal (EDC) is above the threshold, while at the same time the flexor muscle signal is smaller than the extensor muscle signal. Note that the saturation level for the EMG signal is 4.5 volts.

robotic glove, we demonstrate that it is possible to use open-loop sEMG signals as a way to detect the intent of the wearer. Specifically, this was shown to be able to successfully monitor muscle contractions in the flexors and extensors so as to regulate the fluidic pressure within the soft robotic glove and provide three functions: grasp, hold and release.

Under a Harvard Medical School IRB-approved protocol, a number of experiments were performed to characterize the assistance provided by the glove. First, in an experiment with a healthy participant, we showed that sEMG signal was significantly reduced during the manipulation of objects in simulated activities of daily living when wearing the glove. In another experiment the glove grasping force and the glove pressure distribution patterns were quantified using pressure mapping. The results showed that the pressure distribution provided by the glove was similar to that provided by a healthy user and that there was sufficient force to assist with activities of daily living. Finally, the system performance was evaluated during simulated activities of daily living on healthy and impaired participants. These preliminary results showed that a healthy participant was able to complete several subtests in the Jebsen hand function test using only the sEMG sensors (i.e. muscle effort – not finger motion) to control the glove. This highlights the potential for the proposed open-loop sEMG logic. It is well known that the sEMG signal strength for patients with neuro-degenerate diseases is different and thus a proof of concept experiment of the system was performed with a patient with muscular dystrophy. In future work, we aim to recruit more participants with weak hand strength. With a larger pool of participants, we aim to investigate different improvements to the actuation for the soft robotic glove design, as well as, investigate the robustness and influence of the control algorithms accounting for muscle fatigue.

VI. ACKNOWLEDGEMENTS

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REFERENCES

[1] R. P. Erhardt, "Developmental hand dysfunction: Theory, assessment, and treatment: Therapy Skill Builders", *Com Skill Buil*, 1994.

[2] M. M. H. P. Janssen, A. Bergsma, A. C. H. Geurts, and I. J. M. de Groot, "Patterns of decline in upper limb function of boys and men with DMD: an international survey," *J. Neurol.*, pp. 1–20, 2014.

[3] J. Liepert, H. Bauder, W. H. R. Miltner, E. Taub, C. Weiller, "Treatment induced Cortical Reorganization after Stroke in Humans", *Stroke*, vol 31, pp 1210-1216, 2000.

[4] H. Krebs, N. Hogan, M. L. Aisen, B. T. Volpe, "Robot-aided Neurorehabilitation", *IEEE Trans. Rehabil. Eng.*, vol 6, pp. 75-87, 1998.

[5] C. D. Takahashi, L. Der-Yeghiaian, V. Le, R. R. Motiwala, and S. C. Cramer, "Robot-based hand motor therapy after stroke," *Brain*, vol. 131, no. 2, pp. 425–437, 2008.

[6] S. L. Wolf, C. J. Winstein, J. P. Miller, E. Taub, G. Uswatte, D. Morris, C. Giuliani, K. E. Light and D. Nichols-Larsen, "Effect of constraint-induced movement therapy on upper extremity function 3 to 9 months after stroke: the EXCITE randomized clinical trial," *Jama*, vol. 296, no. 17, pp. 2095–2104, 2006.

[7] S. Ueki, H. Kawasaki, S. Ito, Y. Nishimoto, M. Abe, T. Aoki, Y. Ishigure, T. Ojika, and T. Mouri, "Development of a hand-assist robot with multi-degrees-of-freedom for rehabilitation therapy," *IEEE/ASME Trans. Mechatronics*, vol. 17, no. 1, pp. 136–146, 2012.

[8] N. G. Kutner, R. Zhang, A. J. Butler, S. L. Wolf, and J. L. Alberts, "Quality-of-life change associated with robotic-assisted therapy to improve hand motor function in patients with subacute stroke: a randomized clinical trial," *Phys. Ther.*, vol. 90, no. 4, pp. 493, 2010.

[9] P. Heo, G. M. Gu, S. Lee, K. Rhee, and J. Kim, "Current hand exoskeleton technologies for rehabilitation and assistive engineering," *Int. J. Precis. Eng. Manuf.*, vol. 13, no. 5, pp. 807–824, May 2012.

[10] P. Maciejasz, J. Eschweiler, K. Gerlach-Hahn, A. Jansen-Troy, S. Leonhardt, and others, "A survey on robotic devices for upper limb rehabilitation," *J. Neuroeng. Rehabil.*, vol. 11, no. 3, 2014.

[11] S. B. Godfrey, A. Ajoudani, M. Catalano, G. Grioli, and A. Bicchi. "A synergy-driven approach to a myoelectric hand," in *IEEE Intern Conf on Rehab Rob (ICORR)*, 2013, pp. 1-6.

[12] H. In, B. B. Kang, M. Sin, and K-J. Cho, "Exo-Glove: Soft wearable robot for the hand using soft tendon routing system," *IEEE Robotics Automation Magazine*, vol. 22, no. 1, 2015.

[13] Y. Kadowaki, T. Noritsugu, M. Takaiwa, D. Sasaki, and M. Kato. "Development of soft power-assist glove and control based on human intent," *J of Robo and Mechatr*, vol. 23, no. 2, pp. 281, 2011.

[14] H. K. Yap, J. H.. Lim, F. Nasrallah, J. C. H. Goh, and R. C. H. Yeow, "A Soft Exoskeleton for Hand Assistive and Rehabilitation Application using Pneumatic Actuators with Variable Stiffness," in *IEEE Intern Confon Roband Autom (ICRA)*, 2015.

[15] F. Vanoglio, A. Luisa, F. Garofali, and C. Mora, "Evaluation of the effectiveness of Gloreha (Hand Rehabilitation Glove) on hemiplegic patients. Pilot study," in *XIII Congress of Italian Society of Neurorehabilitation*, Bari, Italy, 2013.

[16] K. Tadano, M. Akai, K. Kadota, and K. Kawashima, "Development of grip amplified glove using bi-articular mechanism with pneumatic artificial rubber muscle," in *IEEE International Conference on Robotics and Automation (ICRA)*, 2010, pp. 2363-2368.

[17] [16] A. Chiri, N. Vitiello, F. Giovacchini, S. Roccella, F. Vecchi, and M. C. Carrozza, "Mechatronic design and characterization of the index finger module of a hand exoskeleton for post-stroke rehabilitation," *IEEE/ASME Transactions on Mechatronics*, vol. 17, pp. 884-894, 2012.

[18] L. Dovat, O. Lambercy, R. Gassert, T. Maeder, T. Milner, T. C. Leong, and E. Burdet, "HandCARE: a cable-actuated rehabilitation system to train hand function after stroke," *IEEE Trans. neural Syst. Rehabil. Eng.*, vol. 16, no. 6, pp. 582–591, 2008.

[19] P. M. Aubin, H. Sallum, C. Walsh, and A. Correia, "A Pediatric Robotic Thumb Exoskeleton for at-Home Rehabilitation," in *IEEE Inter. Conf. Rehab. Robot.(ICORR)*, 2013.

[20] P. Polygerinos, K. C. Galloway, Emily Savage, Maxwell Herman, Kathleen O' Donnell and C. J. Walsh, "Soft Robotic Glove for Hand Rehabilitation and Task Specific Training", in *IEEE International Conference on Robotics and Automation (ICRA)*, 2015.

[21] P. Polygerinos, Z. Wang, B. Overvelde, K. Galloway, R. J. Wood, K. Bertoldi, and C. J. Walsh, "*Modeling of Soft Fiber Reinforced Bending Actuators*," *IEEE Trans. Robot.*, 2015.

[22] P. Polygerinos, Z. Wang, K. C. Galloway, R. J. Wood, and C. J. Walsh, "Soft robotic glove for combined assistance and at-home rehabilitation," *Rob. Auton. Syst.*, 2014.

[23] Standards for Reporting EMG data. Journal of Electromyography and Kinesiology, 9(1):III-IV, February 1999.

[24] R.H. Jebsen, N. Taylor, R.B. Trieschmann, L.A. Howard, "An objective and standardized test of hand function." *Arch Phys Med Rehabil*, 50(6): 311-19, 1969.