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Soft Robotic Glove for Hand Rehabilitation and Task Specific Training

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Abstract— **This paper presents advancements in the design of a portable, soft robotic glove for individuals with functional grasp pathologies. The robotic glove leverages soft material actuator technology to safely distribute forces along the length of the finger and provide active flexion and passive extension. These actuators consist of molded elastomeric bladders with anisotropic fiber reinforcements that produce specific bending, twisting, and extending trajectories upon fluid pressurization. In particular, we present a method for customizing a soft actuator to a wearer's biomechanics and demonstrate in a motion capture system that the ranges of motion (ROM) of the two are nearly equivalent. The active ROM of the glove is further evaluated using the Kapandji test. Lastly, in a case study, we present preliminary results of a patient with very weak hand strength performing a timed Box-and-Block test with and without the soft robotic glove.**

I. INTRODUCTION

In the US, there are approximately four million chronic stroke survivors suffering from hemiparesis or similar conditions, over 200,000 spinal cord injury (SCI) survivors living with sustained neurological damage, and an estimated 1 of every 5,600 to 7,700 males have Duchenne/Becker muscular dystrophy (DBMD) [1]–[4]. In the majority of these cases, patients experience either partial or total absence of hand motor ability, and this loss of functionality can greatly restrict activities of daily living (ADL) and considerably reduce quality of life [3]. Physical therapy to improve hand function often involves repetitive task practice (RTP) rehabilitation which requires breaking down a task into discrete components and practicing these individual movements, normally with the assistance of an occupational therapist, to improve hand strength, accuracy, and range of motion [3], [5]. In terms of function, repetitive rehabilitation tasks are not sufficient to increase motor cortical representations in the human brain. However, task specific training with the affected hand was shown to reorganize the cortex faster producing better functional improvements [6]. Current rehabilitative methods, however, are costly, slow, and labor-intensive, placing a high demand on the training and availability of the physical therapist [3].

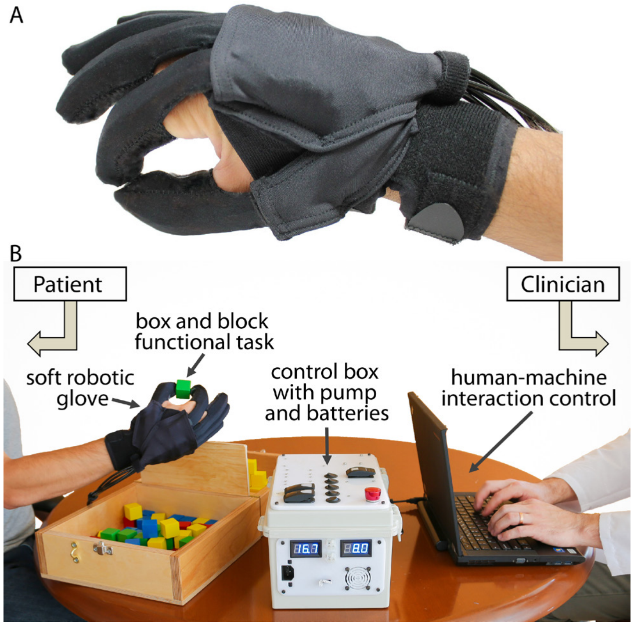

Figure. 1. A. The prototyped hydraulically actuated soft robotic glove. B. Patient-clinician setup that utilizes the soft robotic glove to perform hand rehabilitation scenarios.

Clinical studies indicate that hand impaired patients who use robotic assistance when performing intense repetitive movements show significant improvement in hand motor functionality when compared to patients without robotic assistance [3], [5], [7], [8]. Currently, there are a variety of research groups developing robotic rehabilitation systems for the hand that consist of multi-degree-of-freedom exoskeletons; these are summarized in [9], [10]. The rigid designs of these robotic devices provide robust applications capable of exerting high forces and executing challenging rehabilitation scenarios. However, these rigid devices are typically heavy, expensive and require care and time for proper alignment with the biological joints. Thus these devices are typically not suitable for use during simulated ADL, or task specific training, such as the Box-and-Block test, or the Nine-Hole Peg Test. More recently, a number of hand rehabilitation robots have combined soft gloves with motors that drive cables, or used pressurizable soft actuators to support finger motion [9], [10]. Soft actuators offer a new actuation model that combines traditional robot design

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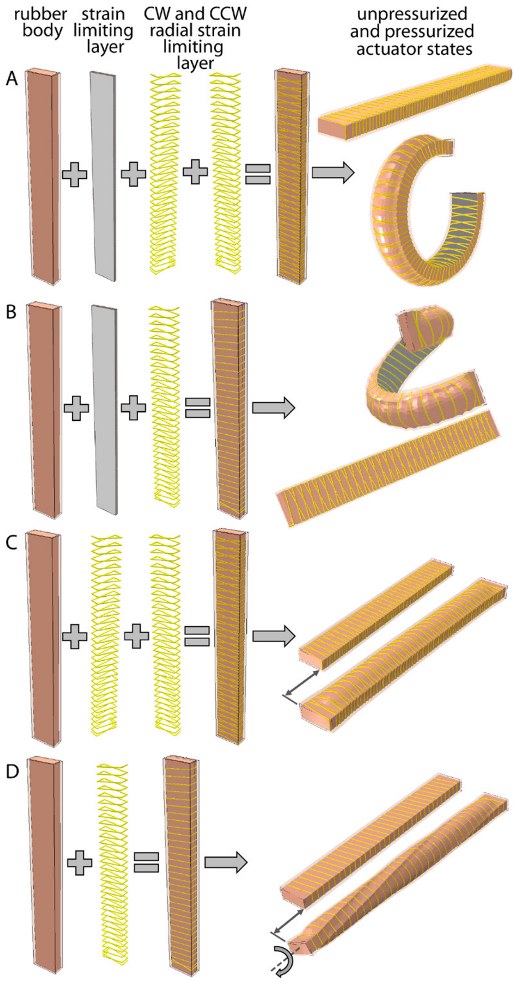


Figure. 2. Combination of fiber-reinforced actuator components and their unpressurized and pressurized behaviors. A. Soft fiber-reinforced bending actuator. B. Soft fiber-reinforced bend-twist actuator. C. Soft fiber-reinforced extending actuator. D. Soft fiber-reinforced extend-twist-actuator.

principles with active soft materials, enabling a novel class of applications [11], [12]. A wearable soft robotic device has the potential to increase the benefits of rehabilitative therapy by providing greater affordability, significant portability, lower weight, easier customization, increased ROM, safer human-robotic interactions, and the ability to conduct task specific training or exercises that simulate ADL.

In this paper, we present our advancements in the design of a hydraulically actuated soft rehabilitation glove [13] that can perform motions similar to those of human fingers (Figure 1A). A system such as this could enable patients with muscular dystrophy, incomplete spinal cord injuries, acute strokes, and in general pathologies that lead to muscle weakness, to perform repetitive rehabilitative tasks, or regain hand function while conducting ADL at home on their own, or in clinic under the supervision of a clinician (Figure 1B). This approach could also offer better patient outcomes through rehabilitative therapy by extending the dose of therapy beyond clinic and into home. The device presented here utilizes inexpensive fiber-reinforced, elastomeric actuators that can be quickly custom-designed to fit the anatomy of individual users (section II). The actuators are integrated into a soft textile glove and mounted to the dorsal side of the hand to recreate the desired motions in a safe and compliant manner (section III). Fluidic pressure sensors measure the internal pressure of soft actuators and provide individual finger control, and a portable control box allows for a variety of pre-set finger motions (section III). Finally, a quantitative and qualitative characterization and evaluation of the soft robotic glove explores patient outcomes of the device (section IV).

II. SOFT SEGMENTED FIBER-REINFORCED ACTUATORS

A. *Actuator Design*

Expanding on prior work [14], the soft actuator design presented in this work consist of thin profile, rectangular elastomeric bladders reinforced with strain limiting materials (i.e. materials with a Young's modulus much larger than the elastomeric bladder, such as fibers) to create anisotropic properties in the bladder wall [14], [15]. Upon fluid pressurization, the bladder will preferentially strain in directions determined by the fiber reinforcements. Figure 2, illustrates four classes of programmable motions using fiber reinforcements, namely bend, bend-twist, extend, and extend-twist. In the example of the bending actuator, a strain limiting layer (e.g. woven material) [16] constrains one face of the bladder from stretching, and a symmetric arrangement of helical fiber threads constrains radial swelling. Upon pressurization, the wall of the actuator with the strain limited layer can be approximated as inextensible (i.e. fixed length), whereas all the other portions of the actuator are allowed to grow lengthwise. This asymmetrical strain along the length of the actuator causes it to bend or curl in the direction of the

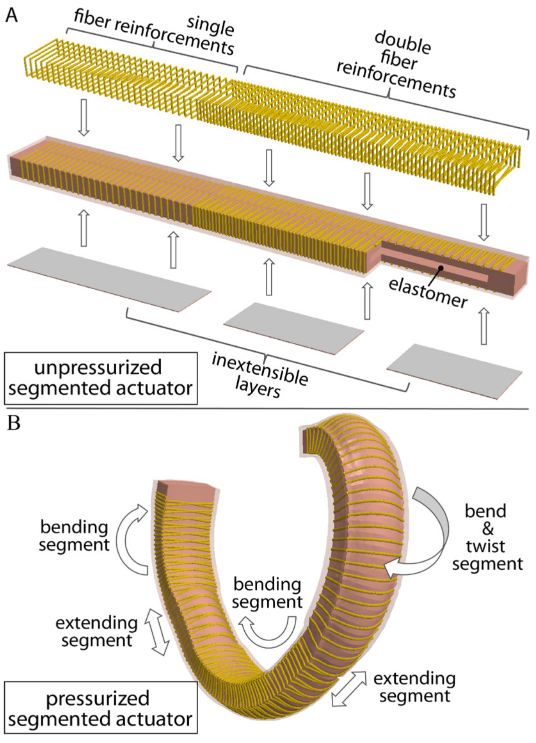


Figure. 3. Illustration of a generic soft segmented fiber-reinforced actuator in: A. exploded view showing fiber reinforcements, elastomer material, and inextensible layers, and B. pressurized view showing a combination of motions.

strain limiting layer. The manufacturing process to make these soft actuators has been described in prior work [13].

These fiber-reinforcement designs also enable more complex motions in which more than one motion can be programmed in series along the length of a single actuator. We define these as multi-segment soft actuators [13],[17]. Figure 3 illustrates this concept, where fiber reinforcements are used to create segments that bend, extend, and bend-twist.

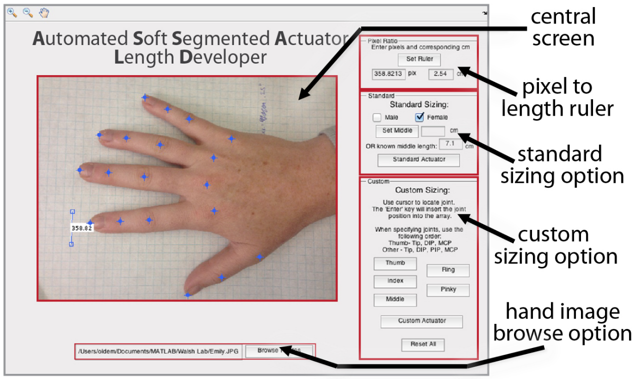
With respect to the hand, multi-segment soft actuators offer a simple method to safely support the full range of motion of each digit. In fact, only two types of multi-segment soft actuators are necessary to support complete hand closure. The first actuator type includes bending and extending segments to support the four fingers closing toward the palmar surface. The extending segments are important for compensating the offset distance between the actuator and the dorsal side of the hand when the finger is flexing. The second actuator type supports the range of motion of the thumb in achieving opposition motion, where the actuator bends above the interphalangeal (IP) and metacarpophalangeal (MCP) joints, extends in between segments and bends/twists along another segment (around the carpometacarpal (CMC) joint).

B. *Custom Actuator Design for Hand Impaired Users*

The general geometry of the multi-segment soft actuators was mainly defined by their efficiency [14] and the finger anatomy of the end-user. In prior work [13], the shape of semi-circular fiber-reinforced actuators was utilized. However, in this work to lower the profile a rectangular actuator design was used which sits on its flat side above each finger. Its cross-sectional width was set to 20 mm to match the width of the average fingers, and height to 7 mm to ensure a low profile.

To provide maximum rehabilitative benefit, the actuator should conform precisely to the finger anatomy of the individual patient by controlling the placement of the inextensible layers. Deviations from the appropriate size may cause distortions in the natural movement of the hand or discomfort in the wearer over continued use, particularly through RTP rehabilitation, task specific training, and rehabilitation through ADL. In the past, finger measurements were taken by hand, and final calculations for corresponding actuator sizes were made from repetitive data input. To reduce error in sizing and assist in the speed and accuracy of fabrication, a Graphical User Interface (GUI) was developed to provide a simple, quick method for determining actuator length and a customizable option that specifies actuator segmentation according to unique patient anatomy.

Figure 4 displays the developed MATLAB interface, which allows the user to upload a photo of the hand to the central screen. For any picture upload, a ratio tool provides a scaling method to convert from pixels to physical length, and the output of the GUI is a table listing the required actuator segment lengths for each finger, as well as the total lengths. A 'Custom Sizing' option allows the user to input locations for the tip, distal interphalangeal (DIP), proximal interphalangeal (PIP) for non-thumb fingers, and metacarpophalangeal (MCP) of the finger using points with manual cursor dragging capabilities. The GUI stores the locations of the points and uses the distances between the points to calculate the actuator segmentation size. A 'Standard Sizing' option, or more generalized option, outputs actuator sizes within approximately 5% accuracy of a custom size, and the only input required is middle finger length. This option outputs reference tables for "Small," "Medium," and "Large" middle finger lengths to determine the actuator segment sizes. The middle finger was chosen as a determinant of size due to a common method for glove sizing systems that relies on middle finger length. The data in these reference tables originate from the results of a participant study (n=25) in which the middle finger was used as a baseline indicator of size to divide participants into three ranked groups: "Small" the bottom third, "Middle" the center third, and "Large" the upper third. The final actuator size in the GUI was averaged within each size grouping of participants. The MATLAB GUI allows for rapid, remote processing of hand images and prompt (< 5 minutes for the 'Custom Sizing' option) output of actuator lengths, reducing the time spent on actuator development.



Enter pixels and corresponding cm

358.8213 pix 2.54 cm

☐ Male ☑ Female

OR known middle length: 7.1 cm

Use cursor to locate joint. The 'Enter' key will insert the joint position into the array.

When specifying joints, use the following order:
Thumb- Tip, DIP, MCP
Other - Tip, DIP, PIP, MCP

/Users/oldem/Documents/MATLAB/Walsh Lab/Emily.JPG

Figure. 4. MATLAB GUI for customized rapid actuator length development. Points with manual cursor dragging capabilities are shown in blue, corresponding to the finger tip, DIP, PIP, and MCP joints.

III. THE HAND REHABILITATION SYSTEM

A. *Design Considerations for a Soft Robotic Glove*

The grasping forces of individuals with hand impairments are found to be reduced in magnitude or, in some cases, nonexistent [18]. Nevertheless, the grasping forces required to manipulate objects that are encountered during daily living do not exceed 10 to 15N [19]. With this in mind, the soft actuators for a hand rehabilitation device do not necessarily need to generate the maximum grip strength of a healthy individual. It is important, however, that the forces generated do not impede natural finger motions or cause discomfort to the wearer. One way to accomplish this is to distribute the forces along the fingers to minimize pressure location points. Besides customizing the soft actuators to the patient finger lengths (section IIB) the textile design of the soft rehabilitation device should allow for some additional customization. The ability to further adjust the textile components can potentially simplify donning and doffing for users with poor hand mobility. Furthermore, all interfacing components of the soft actuators to the hand should be made with compliant, soft materials/textiles that offer minimal mechanical impedance to finger motion when the device is being worn but not operated.

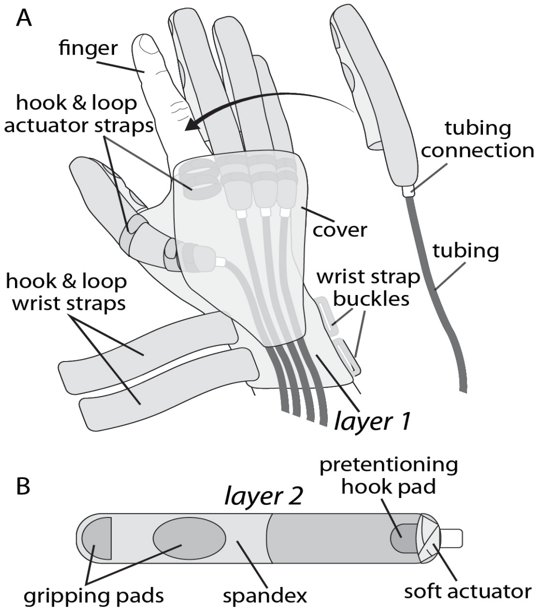


Figure. 5. Schematic of the soft robotic glove outlining the two textile layers that couple the soft actuators to the user's hand.

Another consideration is the weight of the components that are mounted on the hand and arm as any additional weight will likely restrict the movement of an impaired user. Previous devices for the hand have set a design requirement of 0.5Kg for all components on the hand [20], but making them as light as possible will likely be important. The advantage of a soft robotic system is that made of lightweight materials. Any additional electromechanical components (battery, pump, and electronics) required for actuation can be housed in a small table-top control box away from the hand.

To account for the ROM of fingers, the soft actuators should be able to replicate the kinematic movements of the biological fingers as much as possible. Therefore, certain requirements for the device are essential: first, at most three joints are needed for every actuator; second, index, middle, ring, and little finger actuator segments (corresponding to the DIP, PIP and MCP finger joints) should bend together in the same plane; finally, the thumb actuator should bend at least two of its segments in the same plane, having the third bend-twist segment that accounts for the motion created by the CMC joint of the finger (combination of flexion and abduction) bend out of plane.

On the performance side of the robotic glove, the device should be able to approximate an actuation frequency (30 flexing/extending hand cycles/minute) and an operation time that is adequate to enable rehabilitation scenarios. Based on this information, the soft actuators should be able to actuate with a frequency of 0.5Hz while a battery should provide continuous operation for at least two hours.

B. Soft Glove Description

The soft wearable robotic glove features an open palm design and consists of a two-component textile framework that couples the soft actuators to the user's hand. One textile component (labeled *layer 1* in Figure 5A) anchors to the wrist via hook and loop straps and consists of a flexible loop material that covers the dorsal surface of the hand; additional hook and loop straps are used for securing individual actuators. The other textile component (labeled *layer 2* in Figure 5B) houses the soft actuator in stretchable spandex material with an adjacent pocket for the finger, and a hook pad near the actuator base. The glove is fitted to the wearer by securing *layer 1* to the wrist and inserting fingers into the pockets of *layer 2*. Layer 2 can then be pre-tensioned before securing it to *layer 1* with the hook and loop straps. The pretensioning component applies light forces to hold the hand in the extended position. In this design, the pressurized actuator applies forces to flex the fingers, and upon depressurization the soft actuators behave as elastic return springs to return the fingers to the extended hand state.

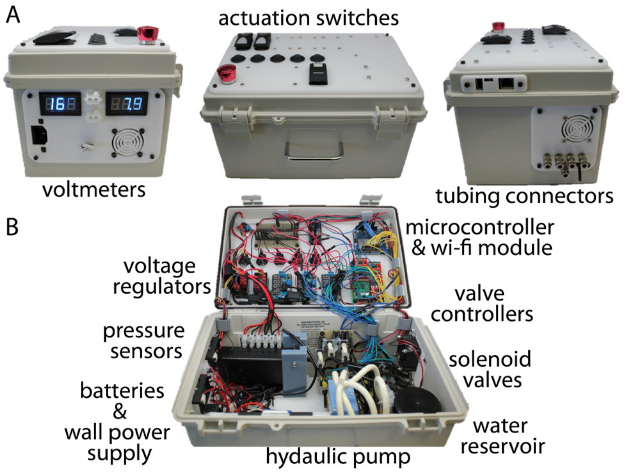


Figure. 6. A. Front and side views of the soft robotic glove control box. B.The soft glove control box showing the electrohydraulic components.

C. Control Box

To minimize additional weight on the hand and arm, the device's hydraulic pump and supporting electro-mechanical components were enclosed into a portable, electrical, table top NEMA box that provides in-and-out protection against water leaks, dust and other hazards. As shown in Figure 6, the control box integrates in a single casing: (a) *the power components*, with: a lithium polymer (Li-Po) battery of 5Ah, and a wall mount power supply; (b) *the electronics*, with: voltage regulators, PWM signal controllers for the valves, and a microcontroller (Arduino Yun, Arduino) with two embedded processors—one that facilitates wireless transmission of data regarding the glove state, and the other that computes the glove control algorithms; and (c) *the hydraulics,* with: fluidic pressure sensors (150PGAA5, Honeywell, Morristown, NJ) for regulation of pressure within each finger actuator, solenoid valves (M series, Gems Sensors & Controls, Plainville, CT), a miniature diaphragm hydraulic pump (LTC series, Parker Hannifin Corp.), and a water reservoir.

The equipped battery is able to provide continuous operation power for about 3 hours, and voltmeters on the side of the control box inform the user when recharging is required. Additionally, mechanical switches are located at the lid of the box, allowing for manual control of the glove's individual finger actuators. An emergency button is located at the lid, offering a fail-safe layer protection in case of an electromechanical malfunction. Lastly, push-to-connect

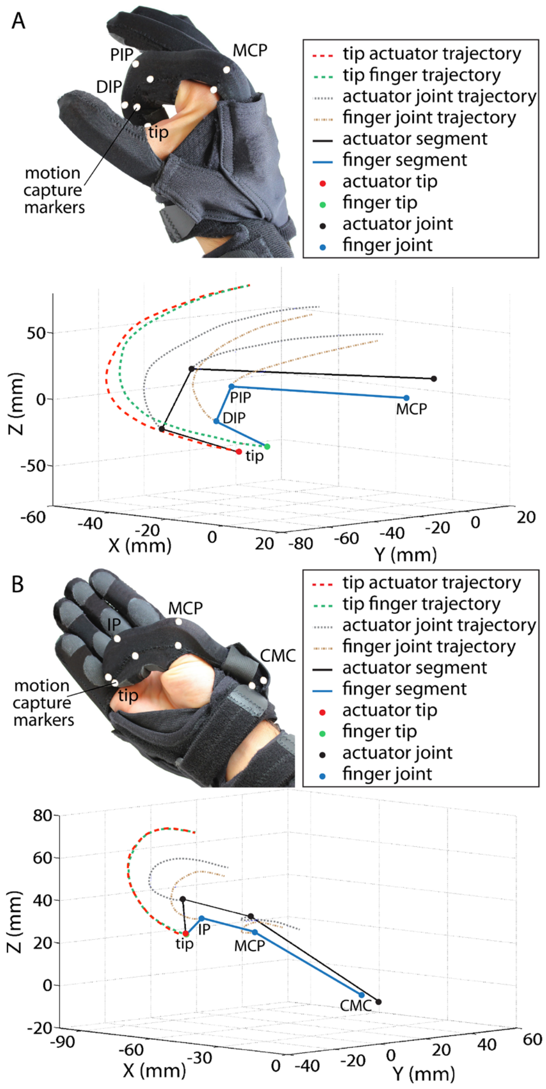


Figure. 7. Motion capture and comparison of joint location and trajectories between the soft segmented actuators and the A. biological index finger, B. biological thumb finger. The results demonstrate that the actuators' segments conform around the fingers and recreate their natural trajectories.

tubing couplings with shut-off valves are located at the side of the box, which enable easy connecting and disconnecting of the soft robotic glove from the control box.

IV. EVALUATION

A. *Actuator Evaluation*

A three dimensional visual motion capture system (Vicon T040, Vicon Motion Systems Ltd. UK) was utilized to evaluate the ability of the soft segmented actuators to conform to the biological finger shape while being pressuized. Reflective motion capture markers were placed on the side of *layer 2* – Figure 5B (dorsal level of finger) at the finger tip, DIP, PIP, and MCP joint locations in order to track the biological index finger. Additional markers were placed at middistance of the equivalent bending segments on the side of the soft segmented actuator (marker loactions are shown in Figure 7A). In this way, the corresponding pairs of markers were positioned in the same vertical plane, able to compare motion paths of joints/segments and shape of finger/actuators at all stages of pressurization. Similarly, markers were placed on the biological thumb finger joints and corresponding actuator segments (Figure 7B).

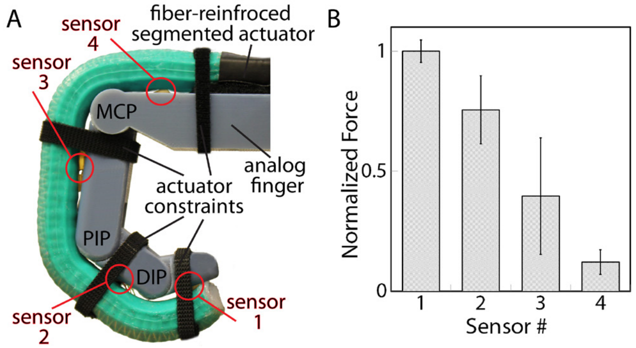


Figure. 8. A. Force sensors are measuring the contact interaction between a segmented fiber-reinforced actuator and an analog of the biological index finger. B. The force distribution pattern along the analog finger.

In a healthy hand participant study, the soft robotic glove was worn by a user who was instucted to keep hand and fingers passive for the duration of the test. The graphs of Figure 7 represent the motion paths of joints and segments for both index and thumb actutor-finger pairs when the actuators were pressurized. The kinematic representation of the actuators and the corresponding biological finger at the final pressurized state are shown in the same figure. It is noted that the observed offsets between actuators and fingers originate from the original offset placement of markers (unpressurized state), which demonstatres how the soft segmented actutors are capable of bending, extending and twisting to smoothly recreate the finger motion and shape of finger when pressurized.

In another test, an analog of a biological finger was fabricated (3D printed) with passive hinge joints and used to illustrate the ability of the soft segmented actuators to distribute forces along the finger length when pressurized. Force sensors (TakkStrip, Takktile LLC, MA) were integrated at the dorsal side of the analog finger (Figure 8A) to record the contact interaction. Above the sensors a soft segmeted actuator was mounted and constrained in the same fashion as the constraints found on the soft robotic glove (section IIIB). Pressurization makes the actuator grow around the analog finger joints while distributed forces flex the finger (Figure 8B).

B. *User Evaluation*

In hand rehabilitation, finger opposition using the thumb is considered one of the most challenging exercises for users with grasping difficulties. Hence, to evaluate the range of motion of the soft robotic glove and its ability to provide gross and pinch grasping motions, the standardized Kapandji test [21] was implemented in a healthy participant. To do so, the soft actuators on the robotic glove were actuated by means of fluidic pressurization. This enabled the guiding of passive biological fingers of the user and recreated opposition motions. In Figure 9B-F, a series of photographs demonstrate the ability of the soft robotic glove to reach each finger and perform the necessary motions as dictated by the standardized test. In addition, Figure 9G-H demonstrates

Figure. 9. Range of motion of the soft robotic glove. A. Pretention of the fabric sleeves surrounding the fiber-reinforced actuators offers full hand extension. B-F. Executing the Kapandji test [21] with the soft robotic glove for thumb range of motion. G. Finger flexion with index finger straight. H. Index finger flexion.

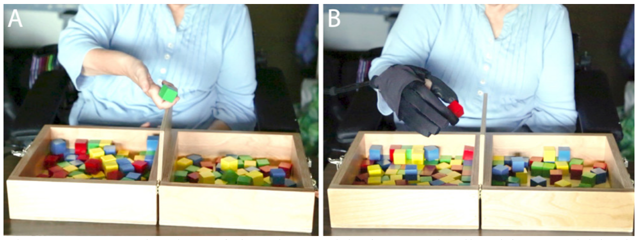


Figure. 10. Evaluation of the glove with the standardized box-and-block hand functional test: A. Without assistance from the soft robotic glove the hand impaired participant is having difficulties grasping the blocks. B. With assistance from the soft wearable glove the participant was able to grasp the blocks faster and with better accuracy.

additional types of motions that can be achieved with the robotic glove. Lastly, the presence of elastic textile materials (section IIIB) confirmed that a gentle pre-tensioning of fingers can enable the hand of the user to maintain an extended state when the actuators were not pressurized (Figure 9A).

A test that assesses unilateral gross manual dexterity, called the standardized Box-and-Block test, was performed on a participant with muscular dystrophy (subject gave informed consent and testing was approved by the Harvard Medical Institutional Review Board (IRB)). Based on this standardize test protocol [22], the impaired participant was asked to use the non-dominant hand to move as many wooden blocks from one compartment of a box to the other over the course of 60 seconds. The same test was repeated having the participant wear the soft robotic glove. The results showed that without the glove the participant was able to move only 10 blocks while showing lack of precise finger motion and hand coordination. With the soft robotic glove, the participant demonstrated a 40% increase in picking blocks and a notable increase in the precision and accuracy of the grasp. Figure 10A-B show both attempts, without and with the glove. Activation of the soft actuator groups was achieved manually by an assistant through mechanical switches located on the control box.

V. CONCLUSION

In this paper, we presented a soft robotic glove designed to assist individuals with functional grasp pathologies perform hand rehabilitation exercises. The hydraulically actuated robotic glove uses soft segmented elastomeric actuators with fiber reinforcements that enabled specific bending, twisting and extending motions. With the aid of a GUI, a method to quickly customize the actuators to the wearer's fingers biomechanics was demonstrated, ensuring a more accurate and comfortable replication of hand ROM and grasping motions. The custom soft actuators were mounted to the dorsal side of the hand with a glove-like textile framework that offered a thin and lightweight profile. To operate the soft robotic glove, a portable hardware control box system was developed. The complete system was evaluated in a series of motion capture experiments and in a Kapandji test and demonstrated that the custom actuators could support the ROM of the biological fingers. Additionally, an analog of a finger with embedded force sensors was fabricated as a platform to demonstrate the ability of the actuators to distribute forces along the fingers. Finally, in a pilot clinical evaluation, the soft robotic glove allowed a participant with reduced hand function to perform faster and more precise functional grasping in a standardized Box-and-Block test.

In future work, a larger study with patients that suffer from hand muscle weakness will be conducted to evaluate and improve further the soft robotic glove design. Sensing schemes will also be investigated to enable the soft robotic glove to estimate user intent and assist in performing grasping motions, while a set of repetitive rehabilitation scenarios will be programmed into the system. Additionally, long term effects from the glove usage will be studied to determine the level of hand motor skills and functional improvement offered thourgh ADL and task specific rehabilitation training.

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