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A Soft Exoskeleton for Hand Assistive and Rehabilitation Application using Pneumatic Actuators with Variable Stiffness

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***Abstract*—In this paper, we present the design of a soft wearable exoskeleton that comprises of a glove embedded with pneumatic actuators of variable stiffness for hand assistive and rehabilitation application. The device is lightweight and easily wearable due to the usage of soft pneumatic actuators. A key feature of the device is the variable stiffness of the actuators at different localities that not only conform to the finger profile during actuation, but also provides customizability for different hand dimensions. The actuators can achieve different bending profiles with variable stiffness implemented at different localities. Therefore, the device is able to perform different hand therapy exercises such as full fist, straight fist, hook fist and table top. The device was characterized in terms of its range of motion and maximum force output. Experiments were conducted to examine the differences between active and passive actuation. The results showed that the device could achieve hand grasping and pinching with acceptable range of motion and force.**

I. INTRODUCTION

Impairment of motor function is the most common problem that surface after developing neurological disorders such as stroke or incurring injury such as post-traumatic arthritis. An individual will lost his or her ability to perform activities of daily living (ADLs) after motor function impairment. This scenario is worse when it happens to the hand. In order to improve hand mobility, patients with hand function impairment are required to undergo continuous passive motion exercises, which involve repetitive tasks such as grasping and opposition motion [1]. Robotic devices with the ability to carry out repetitive tasks have been proposed [2] in order to assist the caregivers in the rehabilitation process and provide a more quantitative process. One example is the hand exoskeleton, which is situated around the hand to guide the finger joints into desired trajectories.

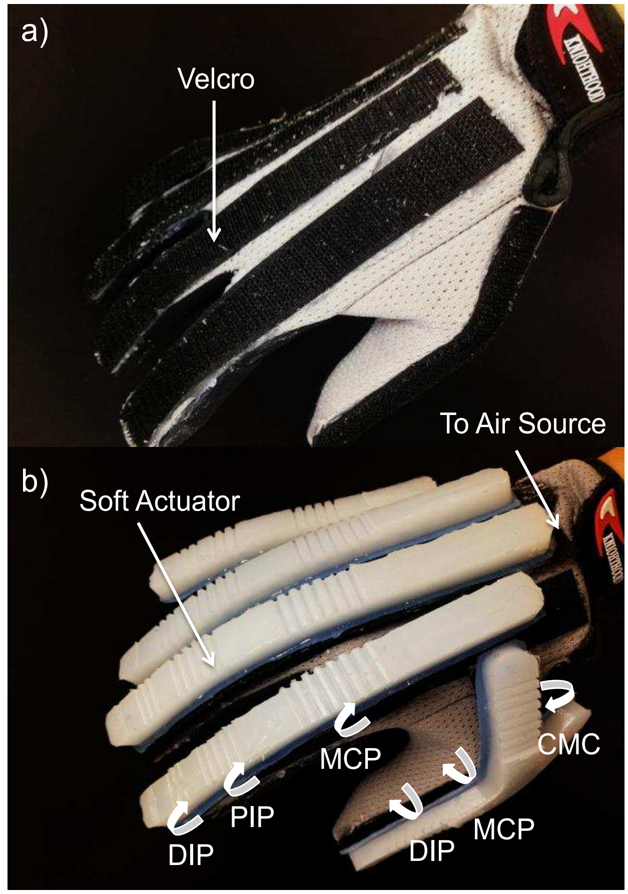

Fig. 1. A ExoGlove prototype. a) Glove is designed with Velcro for easy don and doff. b) Soft actuators are attached to the dorsal side of the glove.

The design of traditional hand exoskeleton device involves cable-driven, linkage-based and pneumatically driven mechanism. Although there are certain advantages derived from these design, such as rigid mechanical body support and linear force transmission that is predictable and easier to control, they also carry several disadvantages when the device interacts with the wearer. For example, in cable driven and linkage-based devices, they are normally bulky and uncomfortable [3]; while in pneumatically driven devices, precise attachment of actuators to the joint rotational centers is required and longer setup time is expected [4]. Moreover, since traditional hand exoskeleton comprises rigid components such as motor and linear actuator, they induce high stresses on the supporting connectors between the exoskeleton and the hand as well as impede the natural movement of joints by constraining their non-actuated DOFs.

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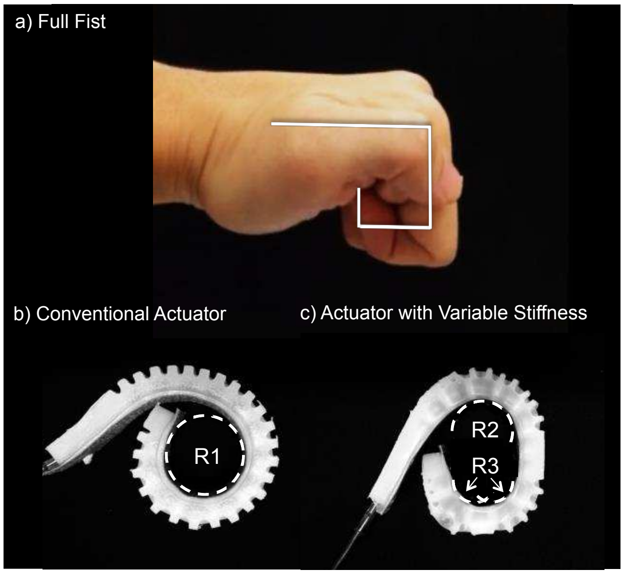

Fig. 2. a) Finger segments' orientation in Full Fist configuration, b) c) Comparison between conventional actuator and actuator designed with variable stiffness, radius of curvature R1 during bending was larger than R2 and R3.

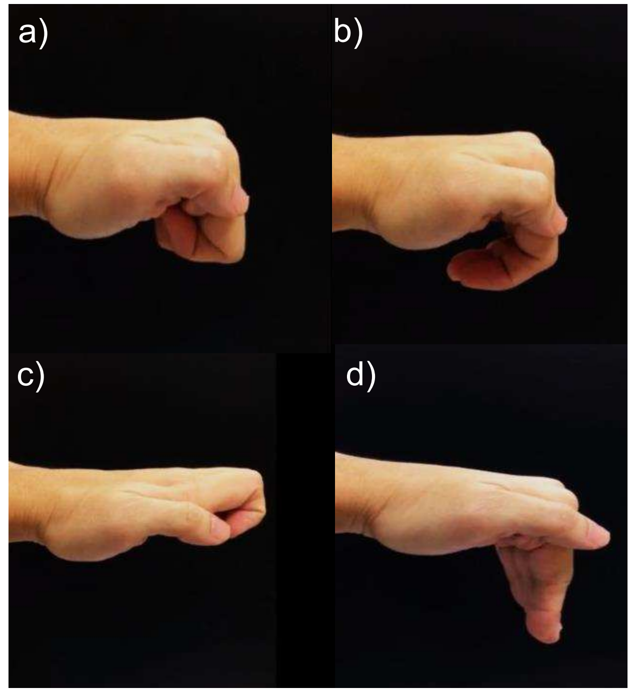

Fig. 3. Typical hand therapy exercises. a) Full Fist, b) Straight Fist, c) Hook Fist, and d) Table Top.

Considering the limitations of current existing devices, various soft exoskeleton devices have been proposed, for example soft elastomeric and pneumatic actuators that guide the movement of the fingers [5-8]. Soft pneumatic actuators are drawing a lot of research interest due to their high compliance and low inherent stiffness. A number of research groups have adopted this kind of approach to develop new soft robotic devices and drive a new paradigm shift of robotics field [9-11]. By using a soft robotics approach to design an exoskeleton, it could lead to greater advantages in rehabilitation by providing customizable motion, higher power to weight ratio, safer interaction between human and robotic devices, as well as lower cost required.

In this paper, we describe the design and characterization of a soft wearable robotic device for assistive and rehabilitation of the impaired hand, called the "ExoGlove". ExoGlove consists of a main body (glove with Velcro straps) as well as customizable pneumatic actuators with variable stiffness (Fig. 1). The key feature of the device is the novel design of the actuator with variable stiffness, which is able to achieve different hand motions required in various physical therapy exercises by adjusting the stiffness of the actuator in different localities. Therefore, the device is highly customizable for different dimensions and therapy exercises.

This device is designed for two modes of application, which are assistive and rehabilitation applications. In assistive mode, the device is able to perform activities of daily living (ADLs) such as hand grasping and pinching, while in rehabilitation mode, the device is able to perform different repetitive tasks in order to achieve continuous passive motion exercises.

II. Design

A. Actuator Design and Fabrication

A number of research groups have developed pneumatic bending actuators such as PneuNets actuator [12] and Fiber-Reinforced actuator [13] for the exoskeleton application of hand and thumb rehabilitation. Although results have shown that these actuators could actuate the fingers, the bending motion profile of these actuators exhibited a circular configuration during actuation and did not conform to the shape of the fingers during flexion (Fig. 2b). Therefore, we developed a new type of bending actuator with variable stiffness, whereby the stiffness of the actuator can be adjusted at different localities, according to the dimensions of the patients' fingers. The actuator bends more at the joints, than at the segments. Moreover, the stiffness of the actuator can also be varied according to different therapy exercises required such as full fist, straight fist, hook fist and table top [14] (Fig. 3).

A two-part 3D-printed reusable mold is required to fabricate actuator with variable stiffness. The lower-part mold (channel mold) is used to create pneumatic channels inside the actuator, which will inflate upon pressurization, while the upper-part mold (feature mold) is used to impose variable stiffness at different localities of the actuator, which decide the bending profile of the actuator.

The design of the feature mold can be customized for patient-specific applications, i.e. the dimension and features at the upper-part mold are designed according to the dimension of the patient's hand as well as different therapy exercises required (Fig 4a, 4b). After confirming the dimension and the exercises required, the feature mold can be designed using CAD software (Dassault Systèmes SolidWorks Corp., USA) and 3D printed (Object500 Connex, Stratasys Ltd., USA). The fabrication process for the actuator with variable stiffness is illustrated in Fig. 4c. The actuator can be fabricated and ready to use in less than one hour.

Upon pressurization, the actuator will bend at the localities that have lowest stiffness. With different stiffness assigned to different localities, the actuator can conform to different shapes, not only a typical circular configuration.

B. *ExoGlove Prototyping*

The overall structure of the device is a glove with soft actuators with variable stiffness attached on the dorsal side. By attaching a total of five actuators on the glove, ExoGlove prototype was built, as shown in Fig. 1. The glove is glued with five Velcro straps, as well as the bottom part of the actuators. Therefore, the actuators can be easily don and doff when required. The total weight of the prototype is approximately 200g. Once the actuators are attached on the glove, the connector tubing are plugged in and connected to the air source.

The attachment of individual actuator depends on the location of finger joints (Distal Interphalangeal, DIP; Proximal Interphalangeal, PIP; and Metacarpophalangeal, MCP for index, middle, ring, and small finger; DIP, PIP and Carpometacarpal, CMC for thumb). The localities with lowest stiffness correspond to the joints and the localities with higher stiffness correspond to the finger segments. Therefore, upon pressurization, the bending at the localities with lowest stiffness will actuate the finger joints, resulting in the change of relative joint angles.

III. RESULTS

A. *Actuator Bending Profiles for Different Exercises*

Different bending profiles of the actuators were shown in Fig. 5. Actuator will bend at the localities that are less stiff. A full fist exercise can be achieved by applying low stiffness at three localities (DIP, PIP & MCP) shown in Fig.5. By allowing bending at PIP and MCP, straight fist exercise can be achieved. Similarly, allowing bending at PIP and DIP will result in a hook fist exercise configuration. A table top exercise can be achieved only when bending at MCP is allowed. Therefore, actuators designed with variable stiffness at different localities can achieve different bending profiles. This unique feature is especially useful in developing appropriate actuators for patient-specific treatment.

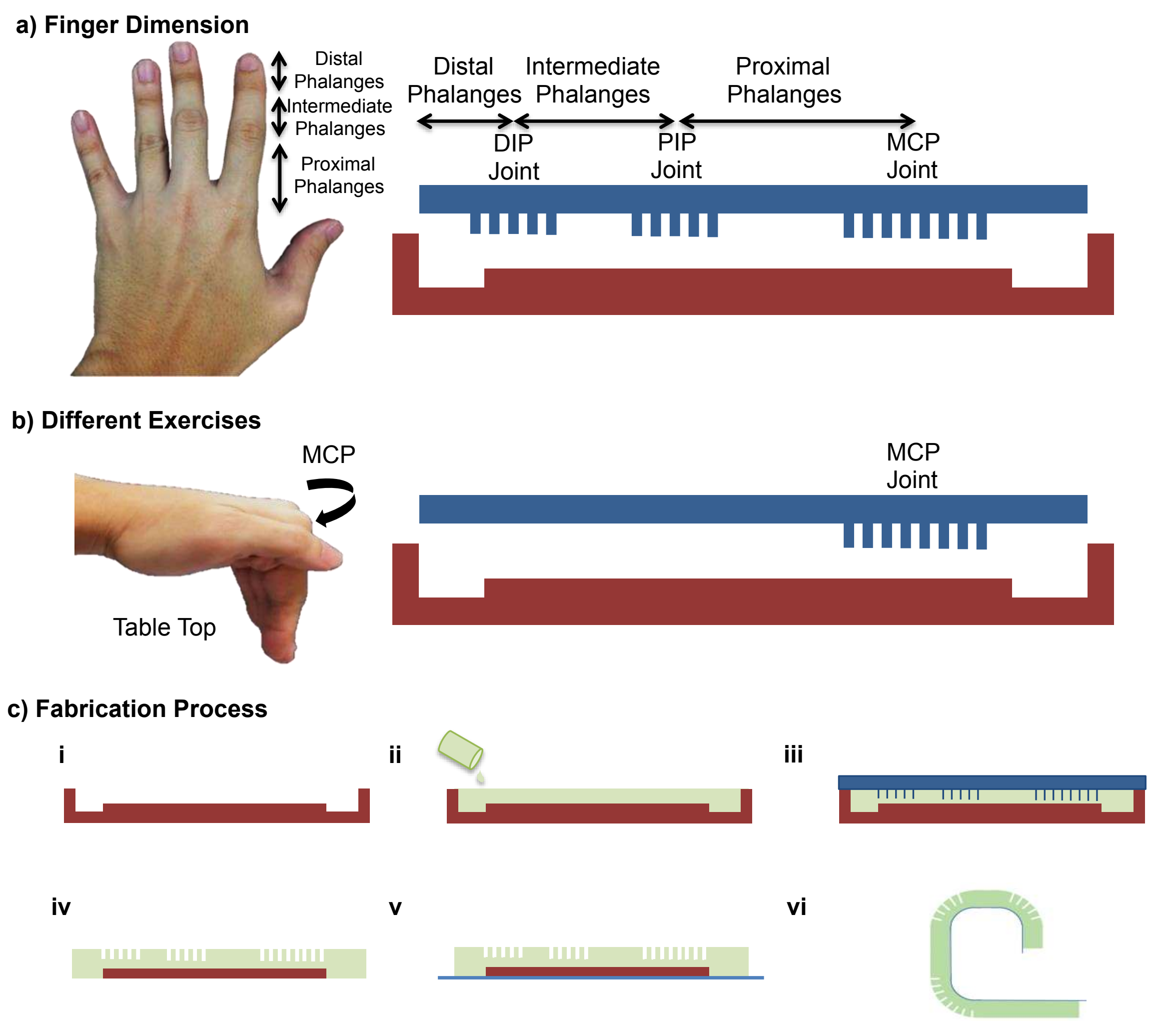

Fig. 4. a) Finger dimension of the patient is obtained before designing the feature mold. b) Feature mold can also be designed according to the exercises required. c) Fabrication process of the actuator, i: Prepare a channel mold, ii: Pour liquid elastomer (DragonSkin10, Smooth-On, Inc.) for the bottom layer, iii: Place the feature mold on top to create variable stiffness at different localities, iv: The ensemble is cured under 60ºC, v: Seal the bottom of the cured structure with strain restraining fabric, vi: The actuator bends at the localities that having lowest stiffness.

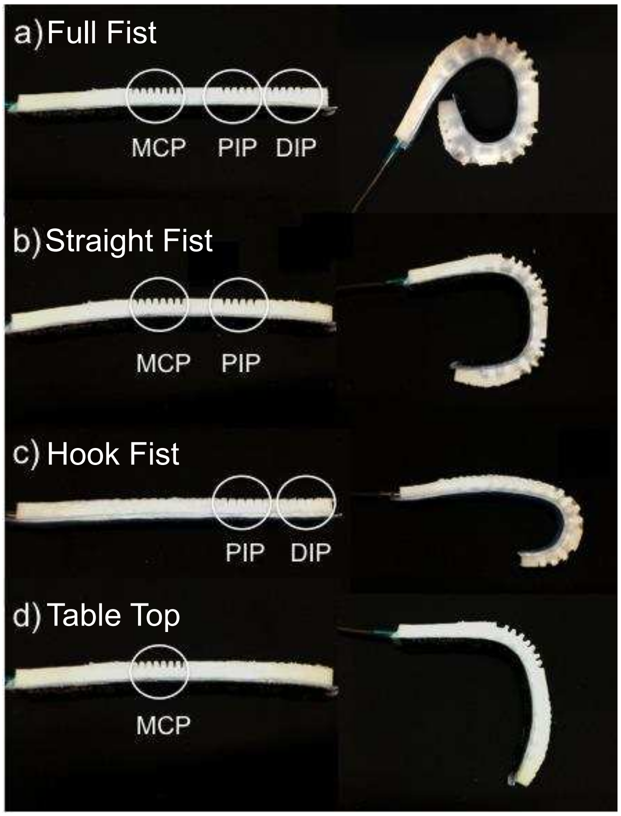

Fig. 5. Bending motion profile of actuators at a) Full Fist, b) Straight Fist, c) Hook Fist, and d) Table Top configuration.

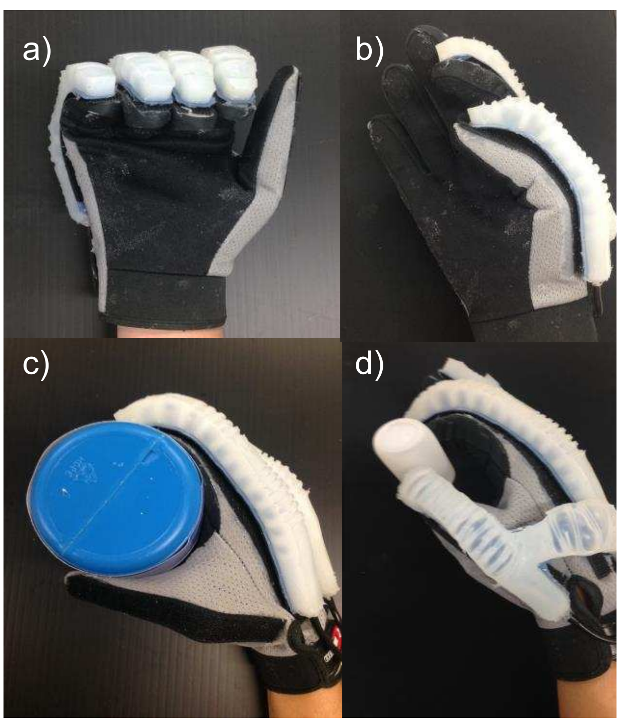

Fig. 6. An ExoGlove prototype in action, a) Four-Finger Flexion, b) Thumb-To-Index Opposition, c) Four-Finger Grasp and d) Pinch.

B. *ExoGlove Characterization*

Fig. 6 illustrates a working ExoGlove prototype. With four actuators corresponding to index, middle, ring and small fingers attached to the glove, the device was able to assist with

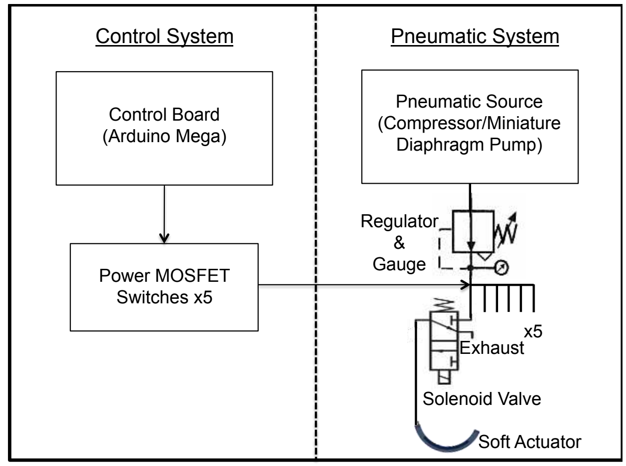

Fig. 7. Schematic of control and pneumatic system.

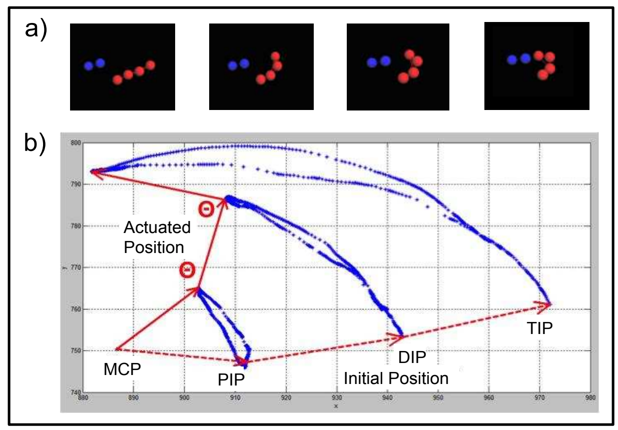

Fig 8. a) Trajectory of reflective markers shown in software interface during hand grasping. b) 2D representation of trajectory of the index finger at initial and actuated position.

the hand grasping action (Fig. 6a, 6c). When a thumb actuator and an index finger actuator were attached and actuated, a pinching (thumb-to-index opposition) action was achieved, as shown in Fig. 6b, 6d. A control system and pneumatic system were assembled in order to allow isolated control of each actuator (Fig. 7). Air can be supplied via a compressor or a miniature diaphragm pump for actuation.

In order to evaluate the performance of ExoGlove, we characterized the prototype in two aspects, which are the range of motion and maximum force output. In this paper, two actions were performed and characterized in the experiment, which are hand grasping and pinching with thumb and index finger.

The range of motion (ROM) experiment was performed with a motion analysis system (Vicon Motion System Ltd., UK). Reflective markers are attached on respective joints on the glove. Eight motion capture cameras were able to capture the trajectories of the markers during actions (Fig. 8). Active grasping and pinching session were conducted in order to obtain the maximum joint angle that a subject can perform actively without the presence of the actuators, followed by passive session, which actions were performed with the assist of actuators. The range of motion of a single joint was

Fig. 9. Forces were obtained with two configurations. a) Sensors were attached on the objects. b) Sensors were attached on the fingertips of the glove.

compared against the maximum joint angle in the active session and the results are shown in Table 1. For grasping action, the DIP achieved 80.3% (50.8°) of the maximum ROM (63.3°) during active session; the PIP achieved 52.9% (45.4° out of 85.9°); and the MCP achieved 68.3% (68.1° out of 99.7°).

For pinching action, the CMC of thumb achieved 54.3% (5.7° out of 10.5°); MCP achieved 91.8% (8.9° out of 9.7°); while for DIP, there was an overshoot of 24.5%, indicated that the tips of the thumb and index finger did not contact during passive session. For the index finger, the DIP achieved 87.6% (28.3° out of 32.3°); the PIP achieved 99.6% (55.0° out of 55.2°); and the MCP achieved 73.6% (36.3° out of 49.3°).

TABLE I. RANGE OF MOTION

Action	Range of Motion		
	Active (°)	***Passive (°)***	***Percentage (%)***
Grasping	DIP: 63.3 PIP: 85.9 MCP: 99.7	DIP: 50.8 PIP: 45.4 MCP: 68.1	DIP: 80.3 PIP: 52.9 MCP: 68.3
Pinching	Index Finger		
	DIP: 32.3 PIP: 55.2 MCP: 49.3	DIP: 28.3 PIP: 55.0 MCP: 36.3	DIP: 87.6 PIP: 99.6 MCP: 73.6
	Thumb		
	DIP: 5.3 MCP: 9.7 CMC: 10.5	DIP: 6.6 MCP: 8.9 CMC: 5.7	DIP:124.5 (Overshoot) MCP: 91.8 CMC:54.3

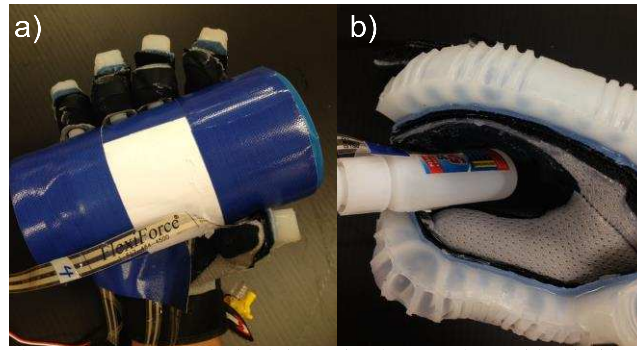

Fig. 10. Forces were obtained during hand a) grasping and b) pinching action.

For the experiment to obtain maximum force output for hand grasping and pinching, flexible force sensors (Flexiforce A201, Tekscan Inc, USA) were used. There were two configurations to obtain the maximum force (Fig.9). In the first configuration, the force sensors were attached on the objects, while for the second configuration; the sensors were attached on the fingertips of the glove at the palmar side. The experimental setup is shown in Fig 10.

The subject was asked to conduct an active session, in which minimum force required to lift the object was recorded. The force was compared against the force output during the passive session, in which the action of lifting object was assisted by the ExoGlove. A 500g object was used for hand grasping and a 100g object was used for hand pinching. The maximum force output during the hand grasping and pinching was compared between these two configurations and the results are shown in Table 2.

TABLE II. MAXIMUM FORCE OUTPUT

Action	Force		
		Active (N)	***Passive (N)***
Grasping	Configuration 1	Thumb: 1.19 Index:2.94 Middle:1.26 Ring:1.37 Small:0.89	Thumb: 1.43 Index:3.59 Middle:1.36 Ring:1.47 Small:1.77
	Configuration 2	Thumb: 0.95 Index:1.31 Middle:1.13 Ring:1.27 Small:0.51	Thumb: 1.66 Index:2.07 Middle:1.39 Ring:1.37 Small:0.63
Pinching	Configuration 1	Thumb: 0.25 Index:1.2	Thumb: 0.89 Index:2.72
	Configuration 2	Thumb: 0.38 Index:1.63	Thumb: 0.51 Index:1.52

160kPa of pressurized air was required in order to achieve a hand grasping action, while for pinching action, slightly lower pressure (120kPa) was required because the index finger actuator did not need to reach its maximum range of motion in order to achieve a pinching action.

For hand grasping, the maximum force occurred at index finger, which was 3.59N in configuration 1 and 2.07N in configuration 2. For hand pinching, the maximum force also occurred at index finger, which was 2.72N in configuration 1 and 1.52N in configuration 2. Both configurations show that the ExoGlove was able to produce force larger than the minimum force required to lift the objects in hand grasping and pinching action. Configuration 1 captured better force signals compared to configuration 2 because in configuration 2, the sensors were attached to the tip of the fingers; however, the contact area between hand and object did not occur at the tip all the time, therefore, less forces were measured in configuration 2.

IV. Challenges

There are few challenges that need to be addressed before tests can be conducted on patients. First challenge is the durability of the soft actuator. The soft actuator is made of hyper elastic material. Hysteresis will be very significant after many cycles and the localities that having low stiffness will become even more compliant. This scenario will make the design of the controller harder because different pressure is needed to achieve same motion after hysteresis. Furthermore, budging problem will also occur and lead to shorter life cycle and material failure in the end. Therefore, the future steps will be to seek for a better material in terms of stability and methods to prevent budging.

User safety is also one of the concerns. A mechanism to detect failure is required as the device is interacting with human subjects and is operated using air source. A failure of pressure regulator might introduce inappropriate pressure into the actuator and cause explosion and failure of actuators in the most serious cases. Failure of actuators must be detected by a control algorithm and stop the device from operating in an unexpected and unsafe manner. Emergency stop button will also be included in future iterations.

Another challenge is that current prototype is not equipped with any feedback system such as sensing elements. Feedback system is required for more accurate control. In order to make the device more robust in terms of autonomy and feedback response to external stimuli, different types of sensors such as pressure sensor, soft elastic joint angle sensor, and force sensor [15] are required. For example, Flexiforce sensor described in Section III can be used in a feedback loop to control the fingertip force.

Additionally, the stiffness of the actuator described in this paper is variable in location and constant in time. Therefore, a single set actuators is capable of supporting only one specific exercise. A new set of actuators is required when patients switch from one exercise to another exercise. Alternative approaches such as designing soft actuators with the ability of controlling bending at the three joints independently will be considered in the future.

V. Conclusions

A soft wearable hand exoskeleton ExoGlove was proposed using pneumatic actuators with variable stiffness at different localities, which can be attached to the glove according to different hand therapy exercises required. Therefore, ExoGlove is able to provide user specific application. This paper shows that the device was able to guide the fingers and create motions such as hand grasping and pinching. The device was characterized in terms of range of motion and force using motion capture system and force sensors. It demonstrated an acceptable range of motion and sufficient force to carry different tasks. Further work is planned to improve force output to actuate finger with increased stiffness, material stability as well as aesthetic.

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