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Design and Characterization of Low-Cost Fabric-Based Flat Pneumatic Actuators for Soft Assistive Glove Application

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***Abstract*— We present the design of low-cost fabric-based flat pneumatic actuators for soft assistive glove application. The soft assistive glove is designed to assist hand impaired patients in performing activities of daily living and rehabilitation. The actuators consist of flexible materials such as fabric and latex bladder. Using zero volume actuation concept, the 2D configuration of the actuators simplifies the manufacturing process and allows the actuators to be more compact. The actuators achieve bi-directional flexion and extension motions. Compared to previously developed inflatable soft actuators, the actuators generate sufficient force and torque to assist in both finger flexion and extension at lower air pressure. Preliminary evaluation results show that the glove is able to provide both active finger flexion and extension assistance for activities of daily living and rehabilitative training.**

I. Introduction

Technological developments in hand exoskeletons over the past decades have enabled their assistance in the rehabilitative process and activities of daily living (ADLs) for patients with impaired motor functions [1]. However, hand exoskeletons still do not receive well acceptance by healthcare institutions and patients due to their own set of problems. Their rigidity, weight and constraint on the non-actuated degrees of freedom (DOFs) of the joints pose complications, stemming from their components such as DC motors, linear actuators, and rigid linkage structures [2, 3]. Thus, the weight as well as the levels of comfort and safety of patients become the major concerns.

In view of this, there is an apparent need for the development of lightweight and wearable hand assistive exoskeletons that may be used both in the clinical setting and brought back home to continue daily therapy or to assist in activities of daily living. The development of wearable robotic exoskeletons serves to provide a more comfortable approach towards addressing this need. Wearable exoskeletons typically utilize compliant materials such as fabric [4, 5], polymer [6] as the interface between the human hand and the actuators, such as cables [7, 8] and soft elastomeric actuators [9, 10]. Eliminating the need for complicated mechanical setups, such an exoskeleton reduces the setup time and the possibility of joint misalignment, at the same time ensures the exoskeleton transparent to hand kinematics. These devices provide a higher chance of user acceptance due to their compactness, affordability and customizability [11, 12].

Amongst these approaches, there has been an increasing amount of interest in inflatable soft actuators due to their low inherent stiffness [13]. Multiple DOFs can be achieved with a single control input, such as air pressurization. Several research groups have developed soft wearable hand exoskeletons using the combination of fabric-based gloves and inflatable soft actuators [14-16]. Several works on soft robotic glove accomplished by Sasaki *et al.* [5, 17], Polygerinos *et al.* [14, 15] and our group [4, 18] have shown encouraging results in both healthy subjects and patients. Sasaki *et al.* have developed a power assist glove that utilizes sheet-like curved rubber muscle for hand grasping application. Polygerinos *et al.* have designed a hydraulically actuated grip glove that utilizes fiber-reinforced actuators mechanically programmable to generate complex motion paths such as bending, twisting and extending to support the kinematics of the finger and thumb. Our group has developed a pneumatically actuated soft robotic glove that utilizes fabric-reinforced elastomeric actuators operating at a lower air pressure as compared to those in earlier studies [4, 18].

The above-mentioned soft robotic gloves were designed to assist in finger flexion and hand grasping upon fluid pressurization. When the actuators are depressurized, the gloves provide passive assistance in finger extension and hand opening via passive stiffness and tensile forces stored in the stretched elastomeric material during pressurization. However, these forces can be insufficient for assisting in hand opening of patients with increased finger flexor tone. Such a situation is observed in the majority of stroke patients, who are not able to extend their fingers and their hand remains clenched due to increased muscle tone in the finger flexors and reduced muscle strength in the finger extensors [19, 20]. Consequently, the aforementioned gloves may not be suitable for this patient group.

In this paper, we present our recent development of a soft assistive glove designed to provide active assistance with both finger flexion and extension for grip-strengthening and hand stretching. The actuators are fabricated from layers of fabric sheets that are commonly used, combined with an inner latex bladder. Based on zero-volume actuation concept, the entire structure is completely flat before inflation. When the actuators are pressurized, they generate forces and torques to support bidirectional finger movements, consisting of finger flexion and extension.

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II. FABRIC-BASED FLAT PNEUMATIC ACTUATORS

A. Actuator Design and Fabrication

Examples of inflatable soft actuators designed for soft assistive glove application include PneuNets actuators [21], fiber-reinforced [9], and fabric-reinforced elastomeric actuators [4]. PneuNets actuators are capable of rapid actuation and achieving full bending at lower pressures as they undergo smaller strain and change in volume during actuation. However, the fabrication process of PneuNets actuators can be very complex and molding the inner geometry of the bellows remains a great challenge. Comparatively, fiber-reinforced and fabric-reinforced elastomeric actuators can be fabricated with greater ease using 3D-printed molds as it allows rapid iterations of different designs. However, when it comes to mass production, designing molds for different soft elastomeric actuators for molding or casting can be rather costly. Additionally, fiber-reinforced and fabric-reinforced elastomeric actuators undergo large strain and changes in volume during actuation, leading to the fatigue of the elastomeric material, affecting the durability of the actuators.

In this paper, we developed a new type of fabric-based flat pneumatic actuators, which are made from layers of fabric including accordion fabric and thermoplastic polyurethane (TPU)-coated fabrics (Fig. 1), with embedded latex bladder, using zero-volume actuation concept proposed by Park *et. al.* [22]. In this concept, the useless empty air chamber volume, typically presented in conventional pneumatic actuator design such as McKibben muscles [23] and soft elastomeric actuators [10], is removed. Thus, the structure is more compact and the resultant 2D configuration also simplifies the manufacturing process.

To create an extension actuator, two layers of thermoplastic urethane (TPU)-coated fabrics are bonded together by mechanical pressure using a heat sealer to create an airtight actuator. To create an air inlet, a pneumatic adaptor is inserted between the two fabric layers prior to the bonding. When inflated, the extension actuator rigidizes and straightens, which exerts an extension torque and pulls the finger into an open state (Fig. 1b).

To create an integrated bi-directional actuator, the extension actuator is further integrated with three other components including an accordion fabric, a latex bladder (perimeter: 60mm) and a non-stretch fabric (Fig. 1c). The accordion fabric and the non-stretch fabric are sewn together (Fig. 1c). Both the latex bladder and the extension actuator are embedded inside the accordion fabric and the non-stretch fabric (Fig. 1d). Upon air pressurization, the inflation of the latex bladder creates a bending motion while the inflation of the extension actuator creates a straightening motion. The integrated actuators generate both flexion and extension torques to support bidirectional movements of the fingers (Fig. 2a).

To support the movement of the thumb, the accordion fabric is sewn in a slanted manner near the proximal part of the actuator (Fig. 2b). During pressurization, the proximal part of the actuator will bend and twist while the distal part of the actuator will bend to support the complex movement of the thumb.

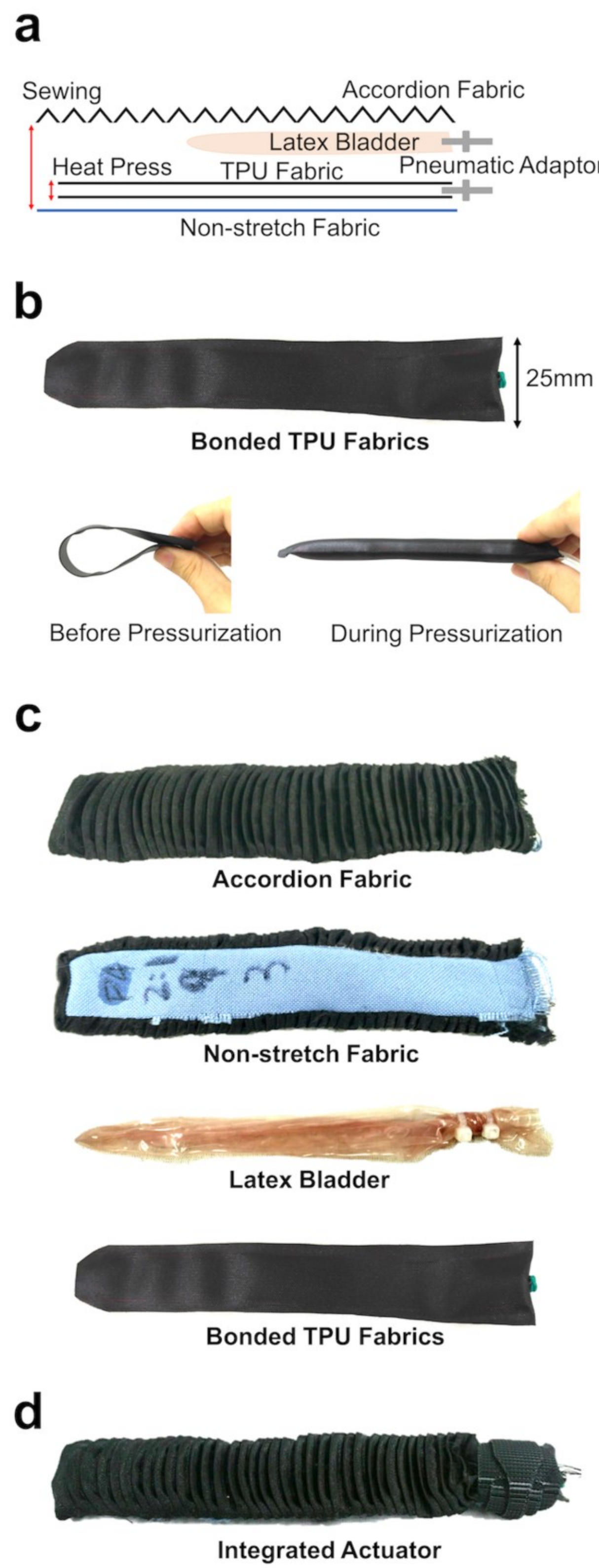

Fig. 1. A fabric-based flat pneumatic actuator. a) Illustration of the components used to fabricate the actuator. b) Extension actuator fabricated from bonding of two TPU fabrics (N420D TPU coated nylon fabric). c) Components used to fabricate d) an integrated actuator. Accordion fabric and non-stretch fabric were sewn together. Latex bladder and bonded TPU fabrics were inserted inside the fabrics.

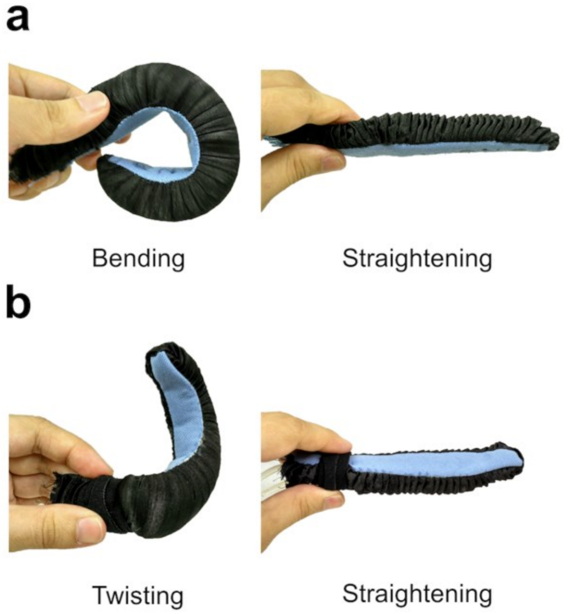

Fig. 2. a) A finger actuator capable of generate bending and straightening motions to support the finger movement. b) A thumb actuator capable of generate twisting and straightening motions to support the thumb movement.

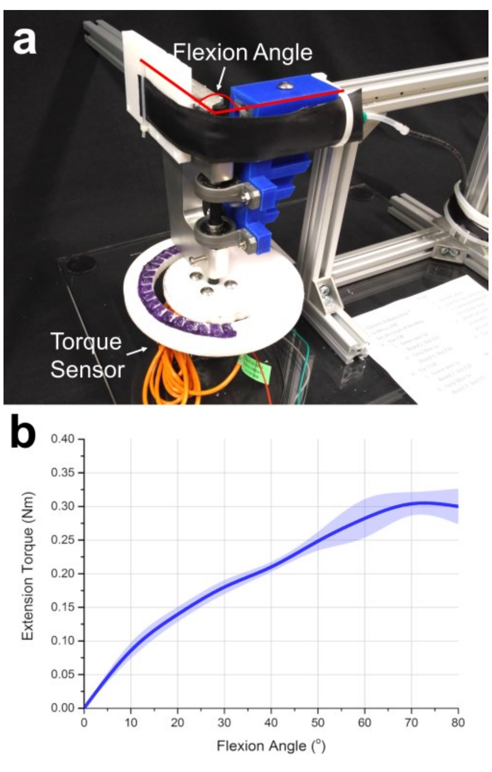

Fig. 3. a) A customized torque rig to measure b) the extension torque generated by the extension actuators at different flexion angles.

B. *Actuator Characterization*

The extension torque generated by the extension actuators were first measured at different flexion angles when they were pressurized at 70kPa. The torque output was obtained using a

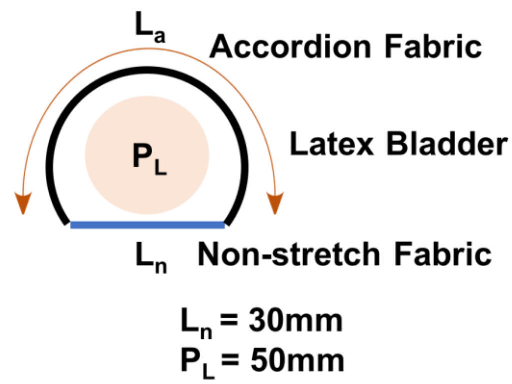

Fig. 4. a) Cross sectional view of the integrated actuators. Parameter of the accordion fabric was varied to examine its effect on the force output. The parameters of the non-stretch fabric and the latex bladder were fixed at 30mm and 50mm.

customized torque rig, where a torque transducer (FT01, Forsentek, China) was installed on the platform (Fig. 3a). The torque rig allowed the measurement of static torque output of the extension actuator at different flexion angles. The torque output increased as the flexion angle increased. The actuator was able to generate an extension torque of 0.31Nm at 70° (Fig. 3b). The total extension torque achieved by four actuators would be 1.24Nm assuming all extension actuators were able to generate same amount of extension torque. According to a previous study, the total flexion torque of stroke patients with spastic finger flexors, which is the sum of the flexion torques at the metacarpophalangeal (MCP) joint of four fingers, is quantified to be within the range of 0.5-4Nm [24]. The results showed that the actuators were able to counteract the total flexion torque that is smaller than 1.24Nm and pull the fingers into an extended state.

The integrated actuator was characterized in terms of their blocked tip force upon pressurization. The parameter of the accordion fabric was varied (30mm, 60mm, 90mm) to examine the effect of the parameter on the force output. The width of the non-stretch fabric was fixed at 30mm (Fig. 4).

The blocked tip force exerted by the actuator was measured over increasing pressures using a customized force measurement platform (Fig. 5a). The system consisted of a compression load cell (FC22, Measurement Specialties Inc, USA) and a mounting platform. The proximal end of the actuator was mounted on the platform and connected to the air source via a connecting tube. The distal end of the actuator was in contact with the load cell. A constraining platform was positioned on top of the actuator, which constrained the curvature of the actuator (Fig. 5b). This force measurement setup was similar to the setup presented in previous studies [9, 15], which could measure the maximum blocked tip force generated by the actuator regardless of the bending angle. The air pressure was increased from 0kPa to 30kPa. The force increased with increased pressure (Fig. 5b).

Accordion fabric with parameter (60mm) closest to the parameter of the latex bladder (50mm) achieved higher force output (9.1N at 30kPa). Compared to previous actuators of similar physical dimension (width:10-30mm, thickness: 6-15mm), the actuators developed in this study achieved similar force output at lower pressure. For example, the fabric-reinforced actuators produce 8-10N of force at 120kPa

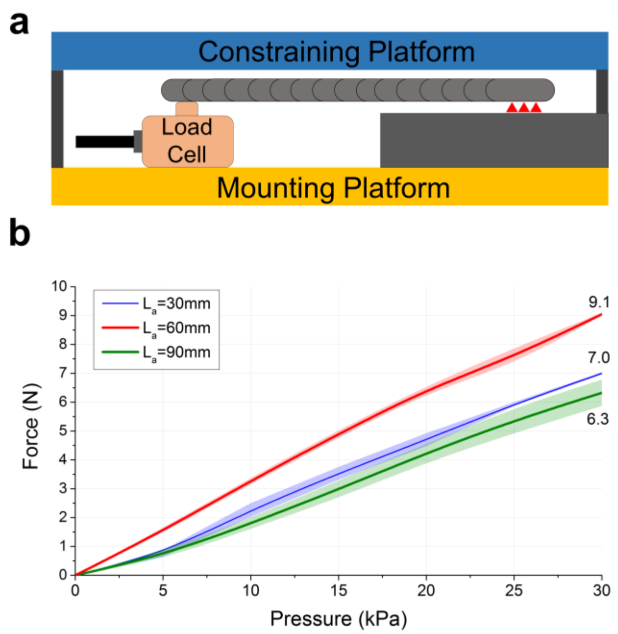

Fig. 5. a) Customized force measurement platform to measure b) the blocked tip force and pressure relationship of the integrated actuators with different dimensions.

Fig. 6. a) An actuator-finger pocket used to interface with actuator and finger. b) Dorsal and c) palmar view of a soft assistive glove prototype.

[4, 18] while the fiber-reinforced actuators achieve similar force output at the pressure range of 275-375kPa [15].

III. Soft Assistive Glove

A. Design Considerations

The glove consists of five actuator-finger pockets attached on the dorsal side (Fig. 6). The glove serves as a compliant interface between the actuators and the hand. It ensures minimal mechanical impedance to the finger motions and allows kinematic transparency when it is being worn. Open palm design is adopted for easy donning and doffing, which would be convenient for stroke patients whose hands are typically clenched slightly. The integrated actuators are inserted into the actuator pockets, which are made from stretchable spandex fabrics. Each integrated actuator is isolated from one another and hence, this enables the actuators to independently assist each finger, which would, subsequently, allow the hand to execute different forms of activities of daily living such as grasping and pinching.

The total weight of the glove is approximately 110g owing to the fully fabric-based design. The glove is much lighter than the glove previously developed by our group (170g) [4] and Kadowaki *et al.* (135g) [17]. Additionally, inflation of the actuators does not add a significant amount of extra weight to the hand as they work under air pressure.

B. Control System

The same pneumatic control system presented in our previous study is used to allow control of individual integrated actuators (Fig. 7). It is able to control the flexion as well as the extension of the actuators. The control system consists of voltage converters and a microcontroller (Arduino Mega, Arduino). The pneumatic system consists of air pressure sensors (MPX5500DP, Freescale, USA) for regulation of air pressure within each actuator, miniature solenoid valves (Flexion Actuators: VQ110U, SMC, Japan; Extension Actuators: X-Valve, Parker, USA), and a miniature diaphragm pneumatic pump (D737-23-01, Parker, USA). PID control scheme is implemented on the microcontroller with a sampling frequency of 100Hz. The control parameters are selected as $K_p = 20$, $K_i = 0.9$ and $K_d = 0.1$. The microcontroller regulates the measured air pressure (P) to track the desired air pressure (P_{ref}) and uses pulse width modulation (PWM) to control the duty cycles of the valves based on the readings from the pressure sensors. The total weight of the table top system is approximately 1.72kg.

C. Assistance with Activities of Daily Living

One healthy participant was recruited to evaluate the feasibility of the glove. For flexion, the actuators were pressurized at 30kPa. For extension, the actuators were pressurized at 70kPa. Figure 8 shows that the glove assisted the participant with finger and thumb flexion as well as activities of daily living such as pinching a small rectangular cube used in box and block test.

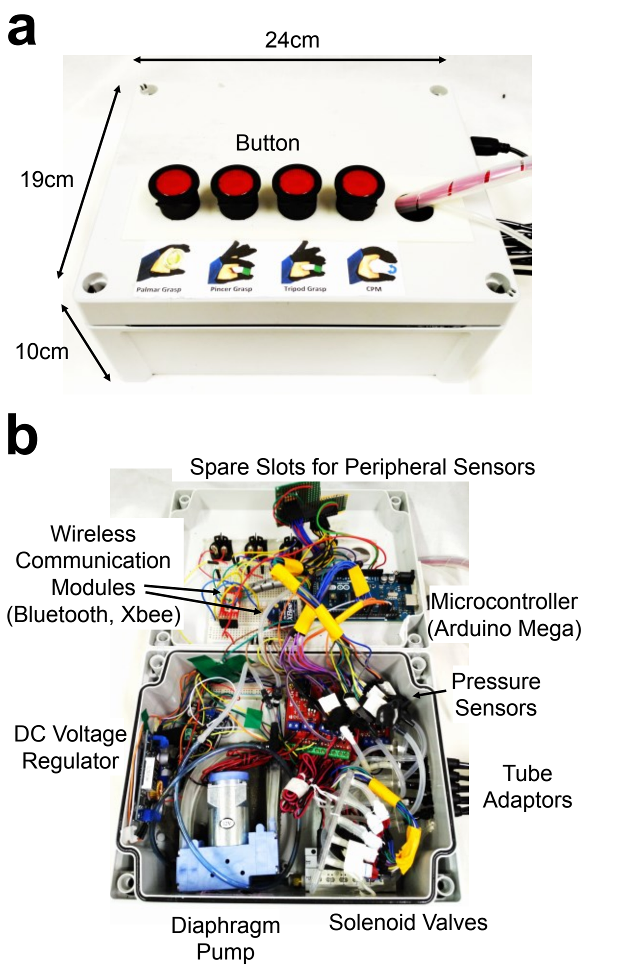

Fig. 7. a) Table top control system with integrated physical buttons. b) Inner view of the control system with the electro-pneumatic components.

IV. Discussions and Conclusion

In this paper, we presented a fabric-based flat pneumatic actuator designed for soft assistive glove application. The fabrication process of the actuators is simpler without the need for mold. Due to the fabric-based design, the glove is much lighter and is of lower profile than the glove presented in previous studies. Experiments were conducted to characterize the extension actuators in terms of the static torque output at different flexion angle. The integrated actuators were characterized in terms of the blocked tip force. A table-top control system was used to control the glove. Finally, we presented initial proof-of-concept results on the feasibility of the glove providing assistance for activities of daily living and rehabilitation.

The characterization results showed that the fabric-based pneumatic actuators achieved higher force output at lower pressure, as compared to previously developed soft actuators. Thus, we can select pumps and valves that operate at lower pressure range and consume less power, which further increases the portability of the whole system. Based on the blocked force experiment, we concluded that accordion fabric with parameter closest to the parameter of the latex bladder achieved the best performance in terms of the force output.

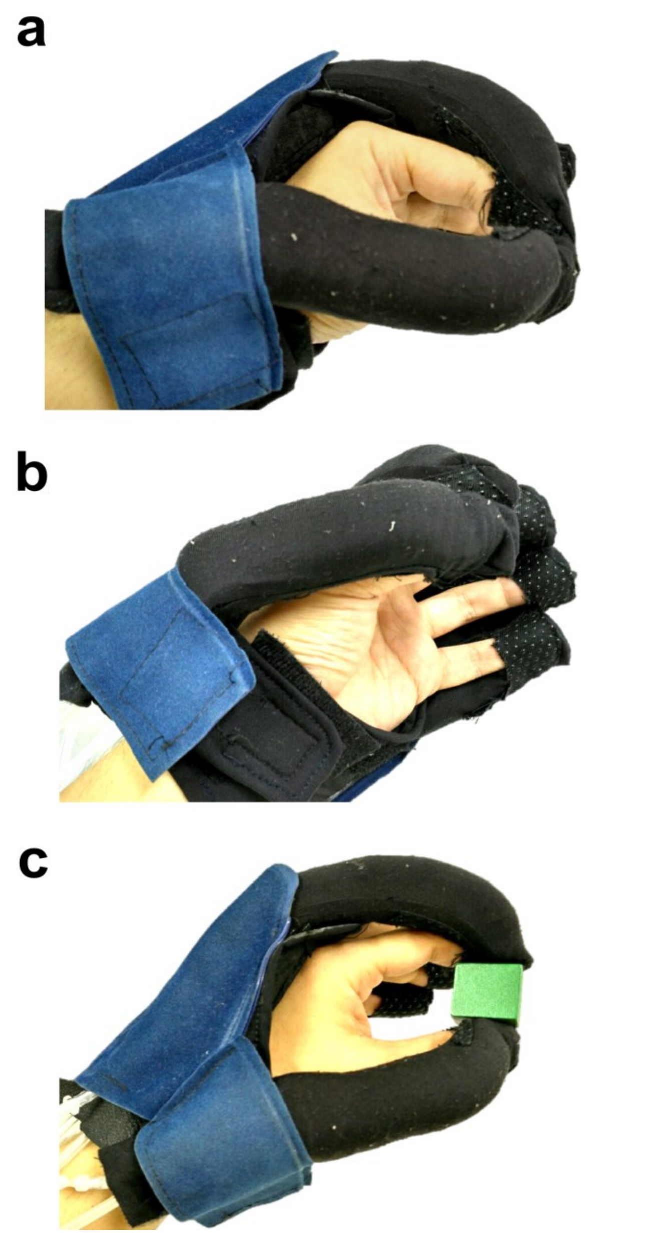

Fig. 8. a) Inflated finger and thumb actuators support finger flexion and thumb flexion. b) Glove-assisted ADL such as pinching a cube.

In this work, the extension actuators were able to generate a total extension torque up to 1.24Nm. The torque might not be sufficient for some patients with increased spasticity, given the torque range of 0.5-4Nm according to previous studies [24]. Although the extension torque can be further increased by increasing air pressure, it is not recommended as high performance pumps will be required and decrease the portability of the whole system. Therefore, the design of the extension actuators will be revisited in order to solve problems such as buckling issues. As the addition of the extension actuators works antagonisticaclly with the flexion actuators, in the future, the antagonist mechanism of the actuators will be studied further to allow a simultaneous adjustment of damping and stiffness to achieve compliant actuation and impedance control with additional force and position sensors.

In the future, the bending capability of the actuators with different dimensions will be studied. Glove-assisted finger range of motion and grip strength will be investigated with more healthy participants and patients. The friction between the latex bladder and fabric might reduce the durability of the actuators. Therefore, fatigue testing will be conducted to study the life cycle of the fabric-based actuators and compare the results with other inflatable actuators. Currently, the addition of the extension actuators requires twice as many valves and air tubes, which increase the weight and the power consumption of the system. Therefore, in the future, instead of controlling individually the extension actuators, all extension actuators will be controlled together using single valve to achieve gross hand opening. Finally, a larger study with hand impaired patients, such as stroke patients and patients with spinal cord injury at C5 and C6 levels will be conducted to improve the glove design and identify ideal and intuitive control strategies for detection of user intent on glove activation and deactivation.

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