Design of a Soft Robotic Glove for Hand Rehabilitation of Stroke Patients With Clenched Fist Deformity Using Inflatable Plastic Actuators

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In this paper, we present a soft robotic glove designed to augment hand rehabilitation for stroke patients with clenched fist deformity. The robotic glove provides active finger extension for hand rehabilitative training, through its embedded inflatable actuators that are fabricated by heat bonding of flexible plastic sheets. Upon pressurization, the actuators inflate, stiffen, and extend the fingers. The actuators were embedded in the finger pockets of a glove. In this work, the device was evaluated in terms of its extension torque generated on the metacarpophalangeal (MCP) joint of a dummy finger model and a healthy subject. A stroke patient with finger spasticity was recruited to demonstrate the feasibility of the device to assist in finger extension. Preliminary results showed that the device was able to generate significant extension torques to provide assistance in finger extension for both healthy and stroke participants. [DOI: 10.1115/1.4033035]

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Introduction

Spastic clenched fist deformity can be commonly observed in stroke survivors due to finger flexor spastic hypertonia and weakness in finger extensors [1]. The deformity further leads to the loss of hand mobility and function. Stroke survivors are required to undergo rehabilitation programs, which consist of repetitive task practice (RTP) in order to restore their hand function [2]. However, these procedures are normally labor-intensive. Therefore, as an alternative to physiotherapist-assisted program, robotic devices such as exoskeletons, which have the ability to assist with repetitive hand movements, have been proposed [3].

Traditional hand exoskeletons consist of rigid components, such as linear actuators, rigid linkages, and motors [4–6]. These components have the capability to exert high forces to execute challenging rehabilitation tasks. However, they constrain the non-actuated degrees-of-freedom (DOFs) of the joints and impede their natural movements. This limits the compatibility, comfort, and safety levels for the patients. More recently, alternative approaches such as cable-driven and pneumatically driven mechanisms have been adopted in order to address the limitations of traditional hand exoskeletons. These mechanisms utilize compliant materials and do not require complicated mechanical setups. Cable-driven exoskeletons involve cables that are connected to electrical motors, which are placed away from the hand [7–9]. These cables transmit the required pulling force to induce finger flexion and extension. In pneumatically driven mechanisms, actuators such as pneumatic artificial muscles [10–13] and soft elastomeric actuators are commonly used. Soft elastomeric actuators have increasingly attracted research interest due to their high compliance and low inherent stiffness [14,15]. They are highly customizable and are able to achieve multiple DOFs with a single input (e.g., fluid pressurization). Several research groups have adopted this approach to develop wearable soft exoskeletons by combining gloves with soft elastomeric actuators [16–20]. The actuators are able to assist in finger flexion upon activation. Upon deactivation, they bring the fingers to the open hand state by acting as rubber return springs.

Although these devices have been demonstrated to be able to replicate many functional grasping modes and assist patients with impaired grasp strength, they are not suitable for the stroke patients, who have clenched fist deformity. Most of stroke patients have the residual ability to voluntarily flex their fingers; however, they are not able to extend their fingers and their hands remain tightly clenched due to increased muscle tone in the finger flexors and weakness in the finger extensors [21]. Since the soft elastomeric actuators actuate in only one direction and passively return to their original state, they are not able to exert enough forces to assist in hand opening for the stroke patients with increased finger flexor tone and joint stiffness.

Several devices have been proposed to provide assistance in hand opening while allowing the wearer to flex the fingers voluntarily [22,23]. These devices utilize elastic materials such as extension springs and elastic cords that are attached to the distal phalanx of each finger at the dorsal side. The tension in the elastic materials increases with increasing hand flexion angle and pull the fingers to the open hand state. However, with increased tension, the resistance of finger flexion increases. Full finger flexion is difficult to achieve, and the range of motion (ROM) is limited. Additionally, they provide only passive assistance and do not actively generate force. Therefore, they are not suitable for patients, who have increased flexor tone and spasticity, and hence, would require higher force to open their hand. On the other hand, Connelly et al. developed a pneumatic glove that provided active extension assistance to each finger [24], while allowing the wearer to flex the finger voluntarily. The device consisted of five air bladders on the palmar side of the glove. Inflation of the air bladder due to pressurization created an extension force which pushed the finger into extension. However, due to the placement of the air bladders on the palmar side and the smooth surface of the air bladders, grasping activities such as fine pincer grasp would be interfered by the air bladders during object manipulation.

Based on the limitations discussed above, the objective of this work was to develop a soft robotic glove for hand rehabilitation of stroke patients with clenched fist deformity. The device was designed to provide active assistance for finger extension and hand opening during the training while allowing the wearer to flex the fingers voluntarily without constraining their natural movements. The device utilized inflatable plastic actuators, which were fabricated by heat bonding of plastic sheets. The actuators were then integrated in a soft glove (Fig. 1). The device was evaluated in terms of the extension torque generated on the MCP joint of a dummy finger model and a healthy subject. Finally, a stroke survivor with finger spasticity was recruited to demonstrate the feasibility of the device to assist in finger extension.

Materials and Methods

Actuator Design and Fabrication. In this work, we proposed an easy and quick fabrication method of soft inflatable plastic actuators (Fig. 2). The actuators were made from electrostatic discharge (ESD) plastic sheets. Two ESD plastic sheets were bonded together by mechanical pressure using a heat sealer in order to create an airtight actuator. This method allowed rapid and more customized fabrication of the actuators according to different hand measurements. A neoprene sponge (733-6731, RS Components, Singapore), which was able to reduce the restriction of airflow within the actuator during finger flexion, was inserted between the plastic sheets. A barbed connector was inserted into one plastic sheet prior to the heat bonding. Latex rubber was inserted to the interface between the plastic and the barbed connector in order to prevent air leakage. Plastic tubing was connected to the barbed connector, and air was supplied from air sources to the actuator via the plastic tubing (Fig. 2).

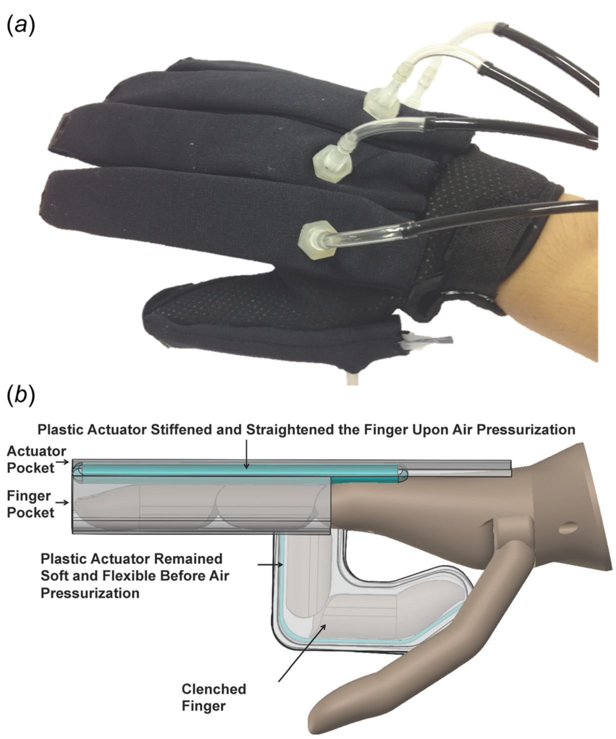

Fig. 1 **(*a*) A soft robotic glove prototype. (*b*) Interior schematic of the soft robotic glove fitted with soft plastic actuators.**

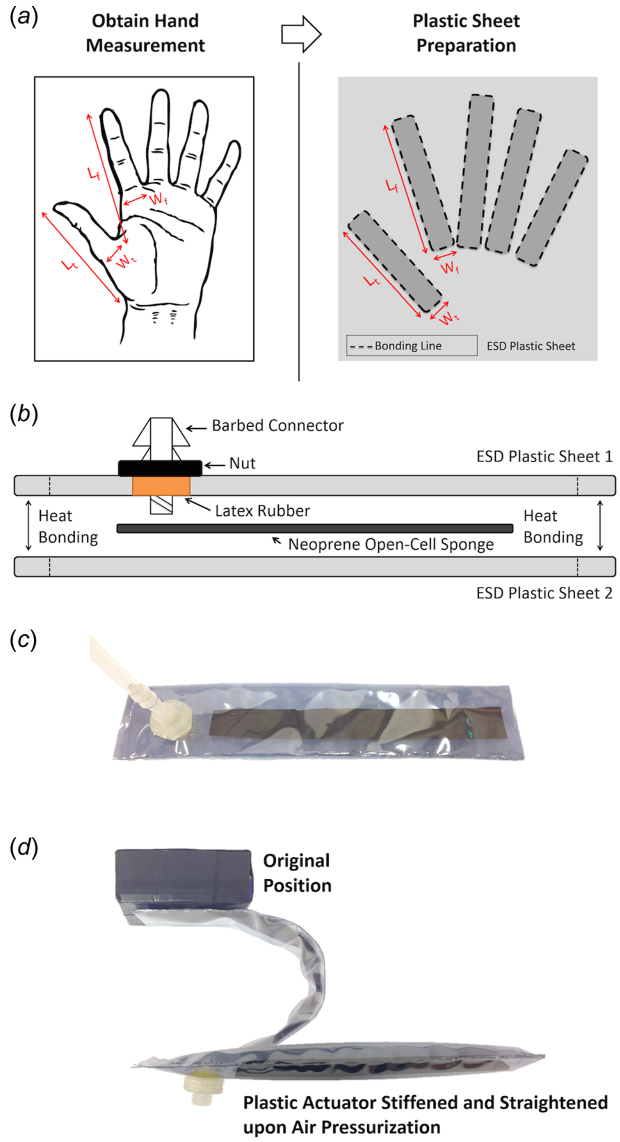

Fig. 2 **(*a*) Components and fabrication process of soft plastic actuator, (*b*) a soft plastic actuator, and (*c*) illustration of a soft plastic actuator before and after pressurization**

Device Integration. The overall structure of the device is a glove with five finger-sized soft plastic actuators embedded on the dorsal side. The glove provides minimal mechanical impedance to the finger motion when it is being worn. The open palm design is adopted for easy donning and doffing of the glove, especially for hands with clenched fist deformity. The soft plastic actuators of different sizes can be easily inserted into the finger pockets. Each actuator is isolated with respect to the others, and thus, the assistance of each finger can be achieved independently, which allows execution of different grasps and release tasks. When the air pressure is removed from the actuators, the wearers can freely flex their fingers and grab real objects. The total weight of the device is approximately 150 g, which is much smaller than the typical design requirement of 450 g for any device on the hand [16]. Due to the low profile and pneumatic nature of the actuators, the inflation of the actuators does not add a significant amount of extra weight to the hand. Additional electromechanical components such as the pneumatic pump and the electronics (microcontroller, valves, and battery) that are required for actuation are integrated into a control box that can be situated away from the hand in order to minimize additional weight on the hand and arm.

An electropneumatic system was assembled and integrated into a control box in order to allow isolated control of each actuator. The control system consisted of voltage regulators and a microcontroller (Arduino Mega, Arduino). The pneumatic system consisted of air pressure sensors (MPX5500DP, Freescale Semiconductor, Inc., TX) for regulation of air pressure within each actuator, miniature solenoid valves (X-Valve, Parker, OH) and a miniature diaphragm pneumatic pump (D761-23-01, Parker, OH). The microcontroller regulated the measured air pressure (P) to track the desired air pressure (P_{ref}) and used pulse width modulation (PWM) to control the activation and deactivation of the valves and pump based on the readings from the pressure sensors (Fig. 3).

Device Evaluation. The device was donned on the ring finger of a dummy finger model that possesses all the three finger joints (distal interphalangeal (DIP), proximal interphalangeal (PIP), and MCP) with sagittal plane ROM similar to that of a typical human finger. Four screws were mounted onto the phalanges and metacarpus of the model hand. To simulate a flexed finger from a clenched hand due to spasticity, extension springs with spring stiffness (2.7 N/mm for MCP and 0.9 N/mm for PIP and DIP) were attached on the palmar side between distal and middle phalanx, between middle and proximal phalanx, and between proximal phalanx and metacarpus (Fig. 4(*a*)). The finger model was originally at the flexed-finger state, representing the clenched fist deformity due to spastic finger flexors [25]. From the known value of the spring stiffness, flexion torque generated by the spring could be calculated. When the actuator inflated and extended the finger, the spring would be extended from its original length. The spring force increased when the spring was extended. Thus, the flexion torque (spring force × moment arm) increased.

A mathematical model was proposed to calculate the flexion torque generated by the spring on the flexed finger. The schematic of the mathematical model at the MCP joint is shown in Fig. 4(*b*). The distance between the MCP joint center and the screw was 20 mm. The extension spring was attached to the screw 18 mm away from the surface of the finger segment. The finger was originally at 55 deg flexion (α). The original angle, θ (half of the angle between the proximal phalanx and metacarpus) was 62.5 deg (Fig. 4(*b*)).

When the spring is extended, the tension in the spring, F, can be calculated by

$$F = k(L_s - L_{\mathrm{So}}) \quad (1)$$

where k is the spring stiffness, L_S is the extended length, and L_{So} is the original length of the spring.

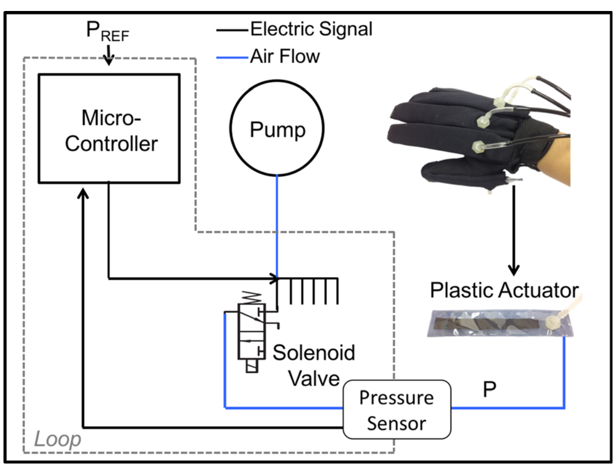

Fig. 3 Schematic diagram of the control scheme for the soft robotic glove

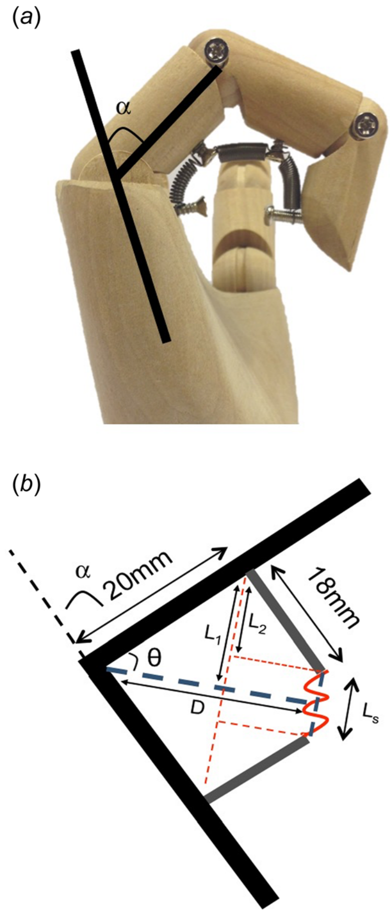

Fig. 4 (*a*) Model hand with extension springs attached and (*b*) schematic of the mathematical model at the MCP joint

The extended length of the extension spring, L_S, can be calculated by the following formulas:

$$L_1 = 20 \sin\theta \quad (2)$$

$$L_2 = 18 \cos\theta \quad (3)$$

$$L_S = 2(L_1 - L_2) = 40 \sin\theta - 36 \cos\theta \quad (4)$$

Based on Eq. (4), the original length of the spring was

$$L_{\mathrm{So}} = 40 \sin 62.5\,\mathrm{deg} - 36 \cos 62.5\,\mathrm{deg} \approx 18.86 \quad (5)$$

The moment arm, D, is calculated by

$$D = 20 \cos\theta + 18 \sin\theta \quad (6)$$

The flexion torque, T_{flex}, at the MCP joint can be expressed as

$$T_{\mathrm{flex}} = FD \quad (7)$$

Combining Eqs. (1) and (4)–(7)

$$T_{\mathrm{flex}} = k(40 \sin\theta - 36 \cos\theta - 18.86)(20 \cos\theta + 18 \sin\theta) \quad (8)$$

Equation (8) can be further simplified as

$$T_{\mathrm{flex}} = k(76 \sin 2\theta - 720 \cos 2\theta - 339.48 \sin\theta - 377.2 \cos\theta) \quad (9)$$

Based on the mathematical model described above, the minimum extension torque that each actuator should generate to counteract the flexion torque (T_{flex}) generated by the spring on the flexed finger when the actuator extended the finger from a flexed position can be expressed as

$$T_{\text{ext}} = T_{\text{flex}} \tag{10}$$

Healthy Participant—Kinematic Evaluation. In order to determine the ROM of the glove, a kinematic experiment was performed with a three-dimensional motion analysis system (Vicon Motion System Ltd., Oxford, UK). Reflective markers were attached on the glove at the fingertip, DIP, PIP, and MCP joint locations. Eight motion capture cameras were able to capture the trajectories of the markers and track the index finger. A healthy subject, who was wearing the glove, was instructed to close his right hand and remain passive for the entire session of the experiment. The actuators extended his fingers and opened his hand when they were pressurized at 100 kPa. The changes of the flexion angle at each finger joint were tracked and analyzed.

Healthy Participant—Kinetic Evaluation. Previous studies have determined the total flexion torque at the MCP joints of four fingers resulting from the spastic stretch reflex and the involuntary flexion torque caused by excessive flexor cocontraction occurred during the attempts of voluntary finger extension in stroke patients [25,26]. The total flexion torque, which typically falls within the range of 0.5–4 N·m, is the sum of the flexion torques at the MCP joints of four fingers.

In order to determine whether the total extension torque generated by the actuators is sufficient to counteract the total flexion torque, a human-subject study was conducted to determine the maximum total extension torque that the actuators can generate. The study protocol was approved by the Institutional Review Board of the National University of Singapore.

The extension torque was obtained by quantifying the amount of resistance to flexion during imposed rotation of the MCP joints of a healthy subject who was wearing the device. This setup was similar to the setup presented by Connelly et al. [24]. The subject's hand was mounted on the experimental device, and the subject was instructed to remain relaxed. The actuators were actuated to the air pressure of 100 kPa. A servomotor (ABRS-5314HTG, Alturn, Taichung, Taiwan) was used to impose the rotation of the MCP joints from 0 deg to 80 deg of MCP flexion at 15 deg/s. A torque transducer (FT01, Forsentek, China) was mounted to the servomotor and recorded the extension torque generated by the device during imposed rotation of the MCP joints (Fig. 5).

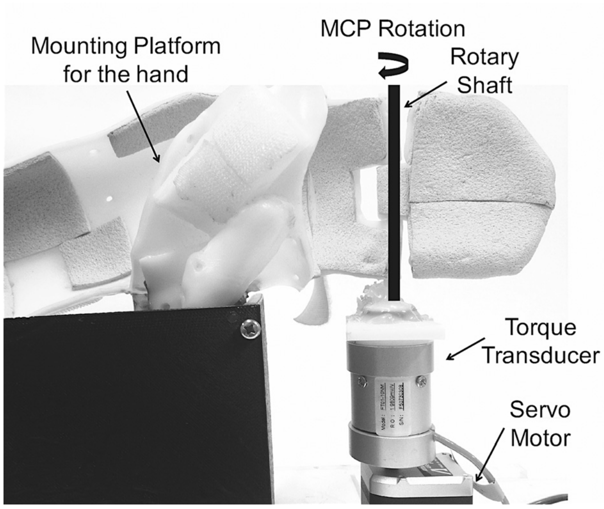

Fig. 5 Schematic of the experimental configuration

Stroke Patient. A stroke patient (male, 43 years old, hemorrhagic stroke) with spastic clenched fist was recruited to evaluate the device (Fig. 6). The patient had a modified Ashworth scale (MAS) finger flexor score of 2. The actuator at the index finger was actuated to the air pressure of 100 kPa.

Results

Device Evaluation. When the actuator extended the finger of the dummy finger model, the angle (θ) changed from 62.5 deg to 90 deg and the flexion angle (α) changed from 55 deg to 0 deg. The extension torque, which was required to counteract the flexion torque at the MCP joint, increased with increasing angle. Figure 7(*a*) shows the relationship between the extension torque (T_{ext}) and the flexion angle (α). The peak flexion torque was 1.03 N·m when the flexion angle reached 0 deg (i.e., the finger was fully extended). Therefore, in order to extend the finger from a flexed position to a fully extended position, the actuator had to generate an extension torque (T_{ext}), with a minimum value of 1.03 N·m, in order to counteract the flexion torque generated by the finger at the MCP joint. This magnitude was similar to the flexion torque resulting from the spastic stretch reflex of a stroke patient with spastic finger flexors [25]. Our results demonstrated that the actuator was able to extend the finger by generating substantial extension torque to counteract the peak flexion torque at the MCP joint (Fig. 7(*b*)).

Healthy Participant—Kinematic Evaluation. Figure 8 illustrates the change in finger flexion angles at DIP, PIP, and MCP joints when the actuators were pressurized at 100 kPa. The kinematic results demonstrated that the device was able to extend the finger from a fully flexed position (MCP: 74.53 deg, PIP: 89.89 deg, and DIP: 23.22 deg) in less than 1 s.

Healthy Participant—Kinetic Evaluation. The MCP extension torque was dependent on the joint angle. When the fingers were fully extended, the actuators exerted minimal force on the fingers. The force and the extension torque increased with increasing MCP flexion. When the actuators were pressurized at 100 kPa, the extension torque generated by the actuators across the MCP joints of four fingers reached a peak of 4.25 N·m at 80 deg of MCP flexion (Fig. 9).

Stroke Patient. Figure 10 shows the photographs of the affected hand wearing the glove at two states: before actuation (0 kPa) and actuators pressurized at 100 kPa. The open palm design allowed easy donning of the glove despite the clenched

Fig. 6 A patient with clenched fist due to finger flexor spastic hypertonia following stroke

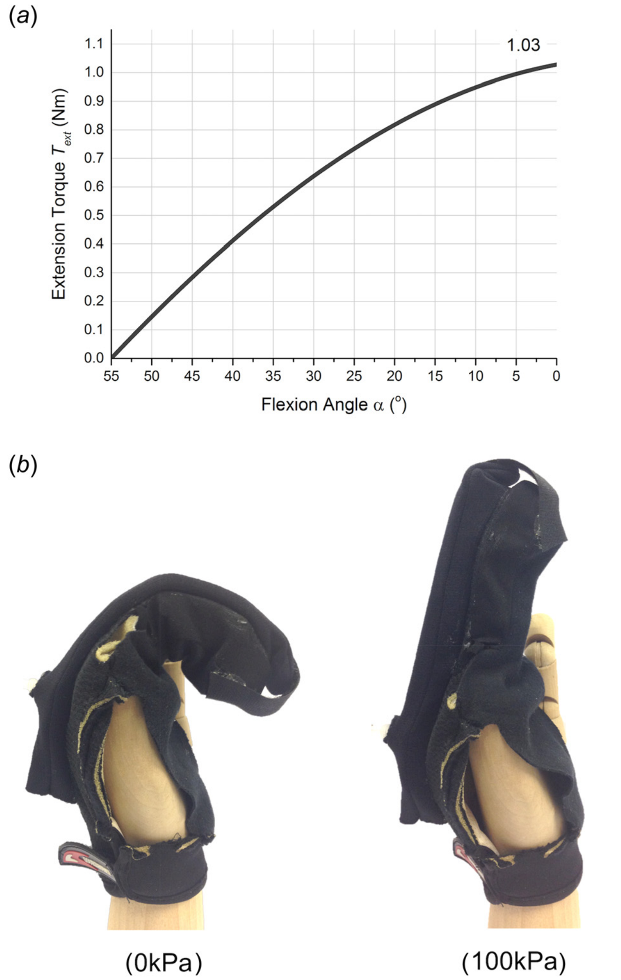

Fig. 7 (*a*) The relationship between the extension torque, T_{ext} and the flexion angle, α. (*b*) Photographs showing the extended finger of the model hand with the assistance of the soft actuator.

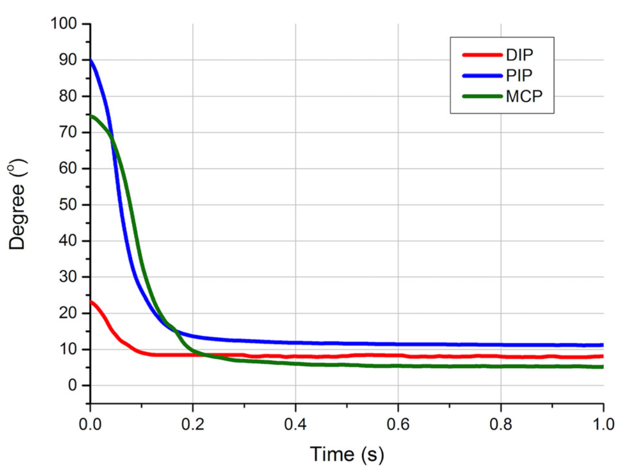

Fig. 8 Change in finger flexion angles at DIP, PIP, and MCP joints when the actuators were pressurized at 100 kPa

hand resulted from increased muscle tone. Preliminary kinematic evaluation demonstrated that the device was able to generate sufficient extension torque to extend the flexed index finger of the patient.

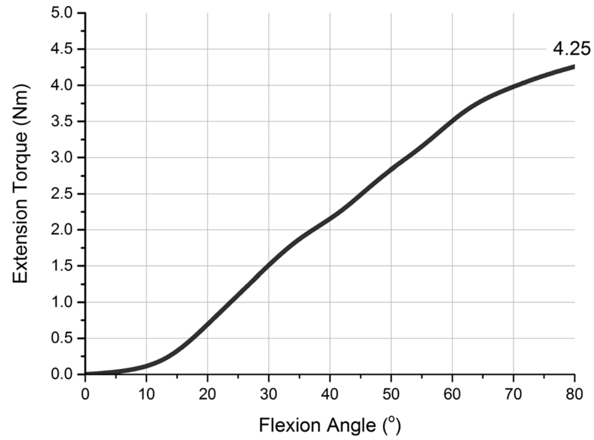

Fig. 9 Extension torque provided by the soft robotic glove at the MCP joint during imposed flexion rotation of MCP joint

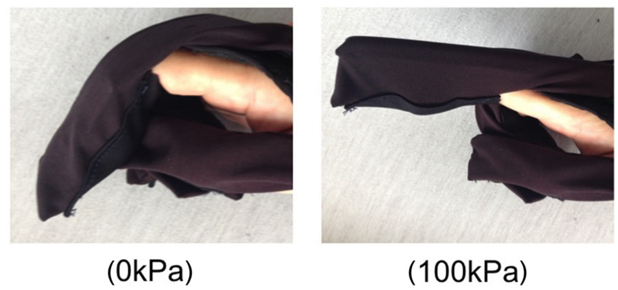

Fig. 10 Photographs showing the extended index finger of the patients with the assistance of the soft robotic glove

Discussion

In this paper, we presented a soft robotic glove for the hand rehabilitation of stroke patients with finger flexor spastic hypertonia. The device is able to assist finger extension in order to facilitate hand movement training, while allowing patients to flex their fingers voluntarily using their residual control. With this device, the patients will be able to open the affected hand for the execution of various functional tasks that require proper hand opening for positioning and releasing manipulated objects.

The glove utilizes soft inflatable actuators that are made from flexible ESD plastic sheets. ESD plastic sheets are made of polycarbonate, which is a thermoplastic material that facilitates heat bonding [27]. This method allows rapid fabrication of the actuators according to the wearer's hand dimensions. The actuators can be easily inserted into the finger pockets that are attached to the dorsal side of the hand. Inflation of the actuators generated well-distributed forces along the finger to extend the finger. The distribution of forces along the finger minimized the localized pressure points that would possibly cause joint hyperextension and subluxation.

Experiments were conducted to evaluate the performances of the actuators in terms of the extension torque generated by the actuators on a dummy finger model and a healthy participant. Based on the dummy finger model, minimum extension torque that each actuator should generate to counteract the flexion torque of the flexed finger could be calculated. The spring constants were selected based on the reported values on the flexion torque in stroke patients [25,26]. Previous studies have quantified the total flexion torque in stroke patients. The total flexion torque, which typically falls within the range of 0.5–4 N·m, is the sum of the flexion torques at the MCP joints of four fingers. MCP joint is a more dominant indicator for the stroke patient group because the extrinsic flexor muscles (flexor digitorum profundus and flexor digitorum superficialis) initiate MCP flexion and produce simultaneous motion at the MCP, PIP, and DIP joints [27]. Therefore, in the stroke patient group, extrinsic flexor muscles that are spastic will have greater effect on the MCP joint and result in larger flexion torque at the MCP joint.

Assuming that all the four fingers have a similar flexion torque, the peak flexion torque at the MCP joint of each finger is between 0.15 and 1 N·m. Therefore, based on Eq. (9) in the mathematical model, a spring constant of 2.7 N/mm was selected for MCP, which corresponded to peak flexion torque of 1.03 N·m. For the PIP and DIP joints, a spring constant of 0.9 N/mm, which corresponded to one third of the peak flexion torque at the MCP joint, was chosen based on the assumption that the flexion torque at the PIP and DIP joints is smaller than that at the MCP joint.

According to the kinematic and kinetic evaluation experiments, the actuators were able to generate a total peak extension torque of 4.25 N·m to extend the fingers from a fully flexed position in less than 1 s. The actuation speed was considered sufficient for normal rehabilitation exercises [16]. The extension torque was also larger than both the flexion torque resulting from the spastic stretch reflex and the involuntary flexion torque caused by excessive flexor cocontraction occurred during the attempts of voluntary finger extension in stroke patients [25,26]. Therefore, the device was able to generate substantial extension torque to counteract the flexion torque resulted from both situations. The extension torque generated by the actuators could be improved with greater pressure. The maximum pressure that the actuators could tolerate was 140 kPa. Finally, a preliminary clinical evaluation on a stroke patient was conducted and the results demonstrated that the glove was able to extend the flexed finger of the patient.

In this work, the glove was controlled by pressure. The desired air pressure (P_{ref}) has to be obtained empirically from different participants. It would be ideal to be able to conduct closed-loop position control. In the future, kinematic tracking elements will be included so that they can help to quantify the movement of the finger joints and provide a more robust closed-loop position control. In the future, the time response of the actuator and the rate of hand opening will also be investigated. The spasticity is velocity related and increasing velocity will lead to higher spasticity in the flexor muscles [25]. Further work is planned to address this issue by modifying the design of the actuator or the controller in order to control and reduce the actuation speed.

Further work is also planned to conduct a larger study with stroke patients with finger flexor spastic hypertonia and different MAS score in order to evaluate and improve the actuator and glove design. Control strategy such as electromyography will be investigated to enable the device to detect and activate accordingly based on user intent. Additionally, a bidirectional soft robotic glove that is capable to provide active flexion and active extension will also be developed to cater for a larger patient population with various hand mobility issues. Moreover, longitudinal intervention studies investigating the functional outcome of stroke patients through rehabilitation training with the device will also be conducted in future.

Acknowledgment

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