LOW COST SOFT ROBOTIC GLOVES FOR AT-HOME REHABILITATION AND DAILY LIVING ACTIVITIES

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Abstract:
Stroke is one of the major reasons which affect the human hand functionality and lead to disability. Different repetitive exercises are used to regain the hand functionality which involves robotic exoskeleton. Soft pneumatic actuators are one of the good alternatives to rigid and fixed exoskeletons for rehabilitation. This paper presents soft robotic gloves fabricated with two different low-cost silicones which can be used in daily living activities and rehabilitation purpose. Soft robotic gloves are light weight and compact. These robotic gloves utilize the pneumatic pressure to flex and extend the human hand. Soft robotic gloves were tested on a healthy object for grasping and rehabilitation ability. Results showed that robotic glove was able to grasping and do the Kapandji test. This work presents an important step toward low cost efficient soft robotic devices for rehabilitation of stroke patients.

Keywords: *Stroke, rehabilitation devices, pneumatic actuators, low cost silicones, soft robotic glove, Kapandji test*

1. Introduction

Human hand is the one of the most useful part in daily living activities. Hand disability caused by stroke effects the quality of life and cause depression and anxiety [1]. Fifteen million people around the world experience stroke annually [2]. Number of stroke patients are increasing in developing countries like Pakistan [3] and Thailand [4]. According to World Health Organization, Kazakhstan has the highest ratio of stroke patients per 100,000 while gulf countries have lowest per 100,000 people [5]. There is high chance of impairment in these patients as compared to death [6]. 60% of the stroke patients do not fully recover at 3 to 6 months after stroke attack [7].

There are different rehabilitation therapies and programs are designed for hand and upper limb disabilities that involve manual and device-based techniques. The developed arm and hand rehabilitation programs are playing significant role in recovery of hand disability [8]. Robot assisted therapy, constraint-induced movement theory, virtual reality training, mental practice and mirror therapy are some of the rehabilitation methods currently being used [9–10]. With these techniques, which

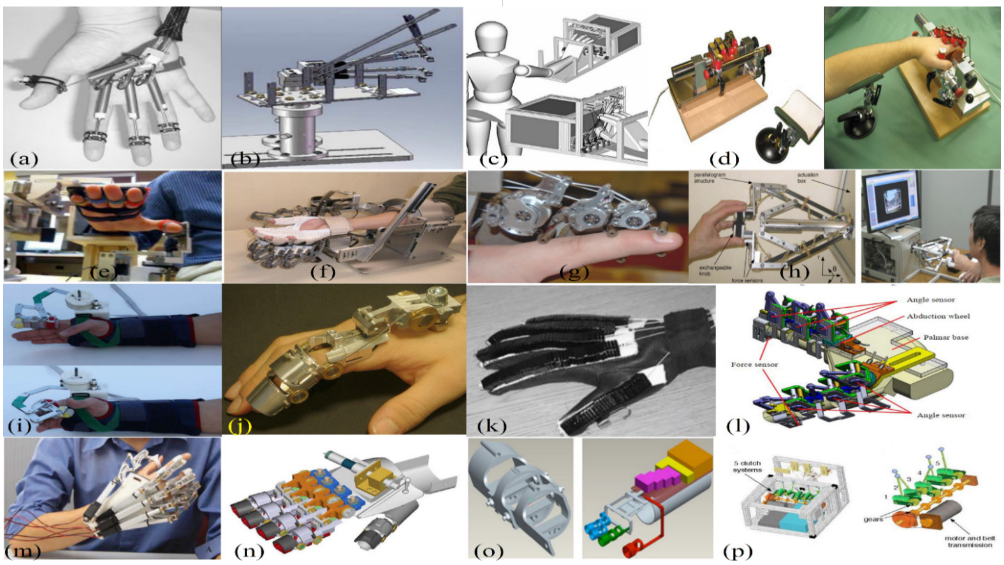

Fig. 1. Rigid body rehabilitation robots: (a) The Rutgers Master II [23], (b) Interactive rehabilitation robot [24], (c) HandCARE [25], (d) Electromechanical trainer [26], (e) HEXORR [27], (f) Finger exoskeleton [24], (g) Thumb exoskeleton [30], (h) Haptic Knob [34], (i) EMG-driven exoskeleton hand robotic [31], (j, n) HANDEXOS [38], (k) Electromyographically driven hand orthosis [42], (l) iHandRehab [39], (m) EMG driven exoskeleton for rehabilitation training, (o) orthotic hand-assistive exoskeleton [33], (p) Cable driven robotic system to train finger after stroke [40]

Reference, Developer	Actuation system	Type of usage	System sensors	Supported movements
The Rutgers Master II-ND [23]	Pneumatic	Rehabilitation, Virtual reality trainings	Hall-effect sensors, infrared sensor	index, middle, ring Finger and thumb
M. Chen [24]	Firgelli linear Actuators	Interactive rehabilitation	Force sensors, EMG's sensor	index, middle, ring and pinky Fingers
HandCARE [25]	Cable Driven , Clutch system	Rehabilitation	Force Sensors	Full hand
Reha-Digit [26]	Electromechanical , Vibration engine	Rehabilitation	Switches	index, middle, ring and pinky Fingers
HEXORR [27]	DC Brushless motor	Rehabilitation	Optical encoder, torque sensor	Full hand
Ismail Hakan Ertas [28]	DC motor , Mechanical designed finger	Rehabilitation	optical encoder, sEMG	One finger at one time
H. Kawasaki [29]	Servo motors, gears	Rehabilitation	Force sensor, Data Glove (Immersion Inc.)	four fingers and a thumb
AFX [30]	DC AKM motors , cable driven mechanism	Rehabilitation	Optical encoders, tension sensors	One finger at one time
K.Y. Tong [31]	Linear Firgelli L12	Rehabilitation	surface EMG	Full Hand
Mulas [32]	Hitec servos HS-805BB, Pulleys, springs	Rehabilitation	EMG	Full Hand
Rotella [33]	Bowden cables	Grasping and pinching	EMG sensor , Force sensor	Full hand
Haptic Knob [34]	Haptic Knob	Rehabilitation	force sensors,	Full Hand
J-Glove [35]	Bowden cable, servomotor,	Rehabilitation	EMG sensor	Full hand
HIFE [36]	Shaft, Motor, gear	Rehabilitation	Data acquisition card, computer application	One finger at one time
Yamaura [37]	Pulleys, RC Servo motor	Rehabilitation	Mechanical switches	One finger at one time
HANDEXOS [38]	Pulleys, DC motor	Rehabilitation	Mechanical switches	One finger at one time
iHandRehab [39]	RE25, RE36 motors, cables	Rehabilitation	Angle and force sensors	Full Hand
Dovat [40]	Cable driven, Clutch system, DC motor	Rehabilitation	"MilliNewton 2 N" force sensors	Full Hand
SCRIPT project [41]	Digit leaf springs, Tension cords	Rehabilitation (Prototype)	Bending sensor, Electric force	Full Hand

Tab. 1. Previously developed hardware systems and their specification

are hand disability can be recovered significantly as compared to manual therapy sessions [11–12].

Robotics assisted rehabilitation techniques have significant result of recovery as compared to manual therapy performed by therapist [13]. Robot assisted training can be used for patient with different level of motor impairment and recovery stage. These training can help patient to get back his muscles power [14]. As compared to conventional therapy, robotic device can provide higher number of dosage (like number of repetitions or practice movements) and high intensity which can be a critical factor in rehabilitation [15]. Robot aided therapy have positive influence on stroke patients and it can improve motor control aspects for long term effects [16]. Recent studies support this hypothesis that rehabilitation with robotic devices is a promising approach in hand therapy [17].

Different studies [18–19–13] showed that the higher number of repetitions increased the speed of rehabilitation and robotic device can provide more speed with accuracy. Rehabilitation robotic device can provide higher number of intense practice sessions with minimum supervision of therapist [19]. Robotic assistance therapy also has a great influence on behavioral gains which can faster the speed of motor recovery after stroke [20]. A study showed that within 3 weeks from starting of robot assisted rehabilitation, patient force generation from effected hand increased by 13.7% [18].

Robotic devices for rehabilitation is a fast growing field in recent years. A lot of robotic devices can be found in literature which show the progress in robotic rehabilitation devices [21] as shown in figure 1. Greater number of these robotic devices are rigid body, heavy and not easy to use as portable device [22]. Some of the devices in literature are presented in table 1.

Rigidness, complexity and heaviness of these systems is an obstacle in using them out of rehabilitation centers and without help of therapist. Lack of compliance (stiffness and softness) is always a problem in rehabilitation devices [43]. Bulkiness of these devices

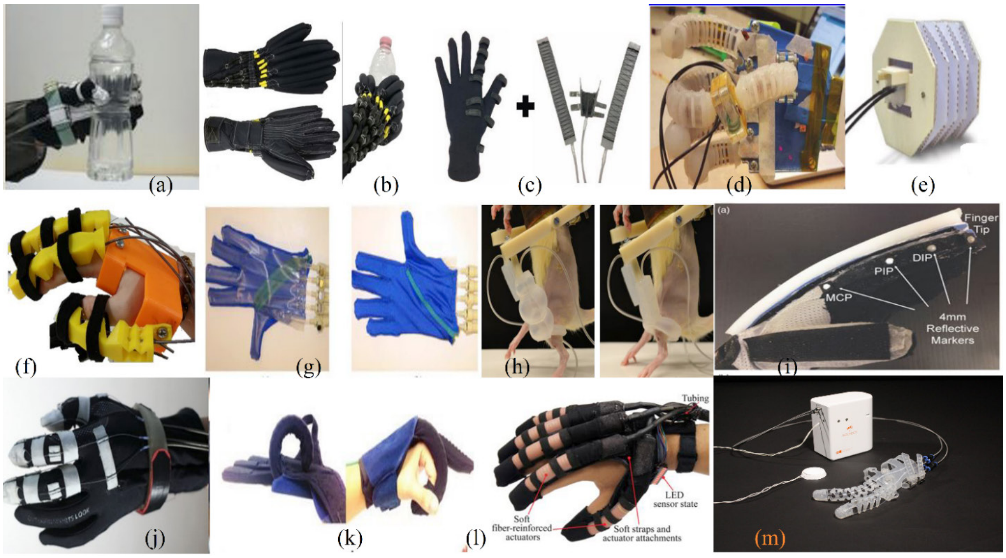

Fig. 2. soft robotic gloves found in literature: (a) Exo-Glove wearable glove base on tendon routing system [45], (b) AirExglove A pneumatic and tendon routing system wearable glove [58], (c) A pneumatic wearable soft robotic glove [59], (d) Shape memory alloys (SMA's) glove [60] (e) Pneumatic actuator with origami shell [53], (f) Kirigami-inspired Flexible robotic hand [52], (g) A pneumatic glove for rehabilitation training [49], (h) gait rehabilitation soft robot [47], (i) Pneumatic robotic glove for rehabilitation [44], (j) Wearable haptic device [61], (k) Pneumatically actuated robotic glove controlled with EMG [62], (l) fluidic actuated soft robotic glove for rehabilitation [56], (m) Exo-Glove poly actuated by tendon driving system [63].

made it uncomfortable for using them for stroke effected hand. Components of these devices like motor and material put more stress on effected parts of the hand. While considering these limitations, various soft exoskeleton robotic devices have been proposed for rehabilitation [44].

In last decade, soft exoskeleton and artificial muscles are being developed and improving the quality of rehabilitation and make it more safe for human-machine interaction. Actuator material and actuation method make it light weight and easy to use for stroke patients. In the literature, these robots are referred as Exo-Glove [45], Exo-Glove Poly [46], Gait Rehabilitation soft robot [47], MR glove [48], PneuGlove [49], RARD [50], GRIPIT [51], Anthropomorphic Robotic Hand [52], Origami Shell based pneumatic actuator [53], Yu She (Actuator) [54], Hong Kai Yap [55], fluidic pressured glove [56] and Soft Robotic Glove [57] as shown in figure 2.

A wearable soft robotic glove can lead to greater improvements of rehabilitation process at home by providing enormous number of degree of freedom and large bending by single input (e.g. fluidic pressure, air pressure). It can provide the safe human-machine interaction because of its soft material used for actuator fabrication and actuation system away from patient body. It can be cheaper as compared to rigid body devices as its material is cheap. Wearable soft glove can be easily portable as it has single actuation energy source (Fluidic reservoir, Air pressure pump) [56]. Moreover, it can be easily used as rehabilitation mode and daily activity mode just by adding a switching for mode change.

Different designs and actuation methods like shape memory alloys (SMA) driven actuators [64], tendon driven actuators [65], Fluid driven actuator [66] and pneumatic actuators [67] has been developed for rehabilitation robotic gloves. Most of the tendon driven cables support only daily living activities and have limited output force and hyperextension. SMA actuators have high operating temperatures ranging from (100°C–500°C). Complex design of SMA actuators made it difficult to use in rehabilitation purposes and daily living activities [64–68]. Pneumatic actuators were selected due to higher stiffness, low weight and simpler design as compared to above mentioned actuators.

This paper presents soft robotic gloves for rehabilitation which used the inexpensive silicon for fabrication of these actuators. Air pressure used as actuation method in these actuators. Air pressure will help the robotic fingers for flexing and extending the hand. Glove will be attached on the dorsal side of hand which helps the patient to feel the objects more naturally. Actuation energy source and electromechanical components are mounted separately to make sure to put the as low as possible burden on human finger.

2. Design

Soft robotic gloves presented in this work operates with pneumatic (air) pressure which provides the grasping and releasing (extension and flexion) of the human hand for rehabilitation practice and daily living activities. The gloves are assembled with soft pneumatic actuators fabricated with low cost silicones and a cotton glove which gives the support for human hand to make it wearable.

Properties	Silicon (RTV 225)	Silicon (RTV4503)	Elastosil M4600
Tensile strength (N/mm2)	≥3.43	5	7
Viscosity at 23° C (mPa s)	15000-17000	35000	12000-20000
Hardness Shore A	28-30	25	20
Tear Strength (N/mm2)	≥22	>20	>20
Operating time (Hour)	0.5	0.5	0.25
Curing time (Hour)	0.5-12	0.5-12	8-12
Mixing ratio	Adjustable	Adjustable	10:1
Density (g/cm3)	-	Approximately 1.16	1.1
Density at 23° in water (g/cm3)	-	1.16	1.1
Elongation at break (%)	≥420	400	800

Tab. 2. Properties of silicon used in fabrication process

2.1. Single Pneumatic Actuator

Soft Pneumatic actuator is based on the design presented by [69] which shows fast actuation. Pneumatic actuator consists of three layers which include extensible top layer which have air chambers, inextensible layer and extensible base layer to enclose both layers as shown in figure (3-a).

Molds with required dimensions were designed in Solidworks (Dassault Systèmes, Waltham, MA, USA) and printed by using 3D printer (Prusa I3) with Polylactic acid (PLA). 3D printed molds are shown in figure 4.

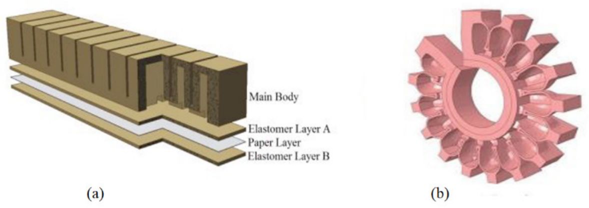

Fig. 3. Soft pneumatic actuator design configuration: (a) different layers of the actuators are labelled, [71] (b) expected bending behavior of the actuator [69] they do so relatively slowly (over seconds.

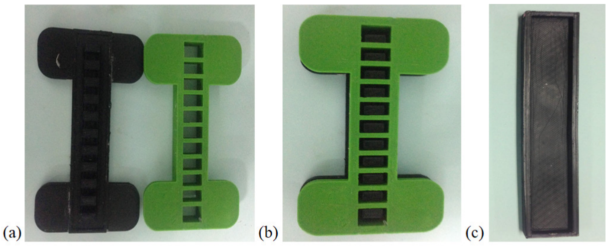

Fig. 4. 3D printed molds for fabrication of pneumatic actuators: (a) upper and lower molds (b) upper and lower molds fitted together (c) Base mold.

3. Fabrication

Soft pneumatic actuator was fabricated with three different locally available low cost materials which include RTV 225(GGC, Taiwan), RTV 4503(GGC, Germany) and Elastosil M4600(WACKER CHEMIE AG, Germany). All three silicones are room temperature curing silicones. Elastosil M4600 have fixed mixing ratio of 10:1 by weight while RTV 225 and RTV 4503 mixing ratios of part A and part B can be adjusting as application requirement, curing time, stiffness and viscosity. Part A is flow-able silicon while Part B is curing agent while both have directly proportional ratio for stiffness, curing time and inversely proportional for viscosity. The material properties comparison is shown in table 2.

Different mixing ratios were experimented for getting the required stiffness, curing time and viscosity for RTV 225 and RTV 4503. Paraffin oil was used to control the concentration level of part A. Table 3 and table 4 shows the mixing ratios of RTV 4503 and RTV 225 respectively for part A, part B (curing agent) and paraffin oil. A range of mixing ratios for part B (curing agent) with part A and paraffin oil were found during the experiments which varies from 1.99–2.98 (g) for RTV 4503 while 1.16–1.55 (g) for RTV 225 presented in table 3 and table 4.

Part A, part B and paraffin oil was stirred with electric mixer (EMS-52, Thai city electric co. ltd, Thailand). The mixture was poured directly into the mold as shown in figure 5-a. Stirring of silicon parts usually produce the bubbles in mixture which cause the leaking in actuator's body. Vacuum chambers or sharp edge objects like needle used for degassing depending on the quantity of air bubbles. In this study, large number of air bubbles were observed after stirring the mixture. A custom made vacuum chamber was used for degassing the mixture. The molds were left for curing for 8–12 hours. Fabrication process of actuators is shown in figure 5. Fabrication process of the pneumatic actuators is described here in details [69].

Silicon (g)	Paraffin Oil (g)	Curing agent (g)
87.31	9.05	3.64
87.94	8.78	3.28
87.52	9.50	2.98
88.57	9.10	2.31
86.98	11.03	1.99
89.51	8.98	1.51
90.01	8.81	1.18

Tab. 3. Mixing ratios of RTV 4503 Silicon elastomer

Silicon (g)	Paraffin Oil (g)	Curing agent (g)
86.34	11.63	2.03
89.56	8.80	1.64
89.59	8.86	1.55
89.12	9.42	1.46
88.56	10.03	1.41
89.96	8.52	1.16
89.67	9.32	1.01

Tab. 4. Mixing ratios of RTV 225 Silicone elastomer

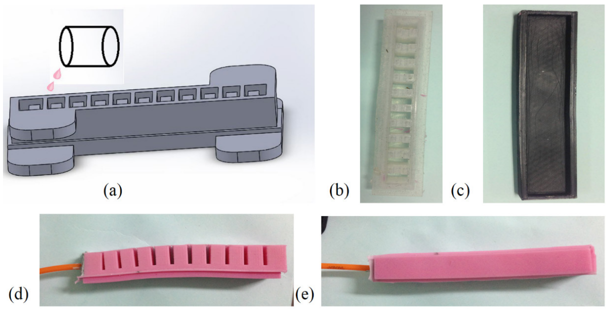

Fig. 5. Fabrication process of single actuator: (a) stirred mixture was poured directly into mold and left for curing (b) fabricated air chamber (top layer) after demolding, (c) base mold, some mixture was poured directly into base and left for curing. Then a paper layer was inserted and poured some more silicon which glued the upper layer. (d) side view of fabricated actuator after inserting the pipe for air supply (e) bottom view of actuator.

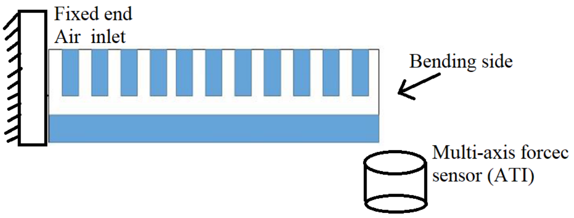

Fig. 6. Experimental setup for blocked force test.

4. Results

For Blocked force test, free travel trajectory test and glove grasping test, a low-cost air pump was used for constant air pressure supply with a pressure sensor (Honeywell, ASDXAVX100PGAA5) and solenoid valve (SMC pneumatics, VDW31-5G-3-01).

4.1. Blocked Test Force Measurement

Blocked force test was conducted to measure the force generated by soft actuators at tip. Blocked force test for evaluating the interaction force of pneumatic actuator is shown in figure 6 where bending end of actuator was blocked by sensor and blocked force was measured. All three actuators were tested. The experimental results are shown in figure 7 where soft actuator fabricated with Elastosil M4600, RTV 225 and RTV 4503 is generating the output force of 1.36N, 1.15N and 1.03N respectively. One of the parameter in blocked force is stiffness of actuator which can be increase by input pressure of the actuator, geometry of actuator and stiffness of material [72]. RTV 4503 and RTV 225 stiffness can be increased or decreased by increasing or decreasing the weight percentage of curing agent. The experimental result of blocked force and input pressure relationship for all three silicones is shown in figure 6.

4.2. Free Travel Trajectory Tracking

The setup for free travel trajectory is shown in figure 8 (a). One of the end was fixed with connecter and air pressure was supplied. There was an initial free travel bending of 49° for Elastosil M4600 fabri-

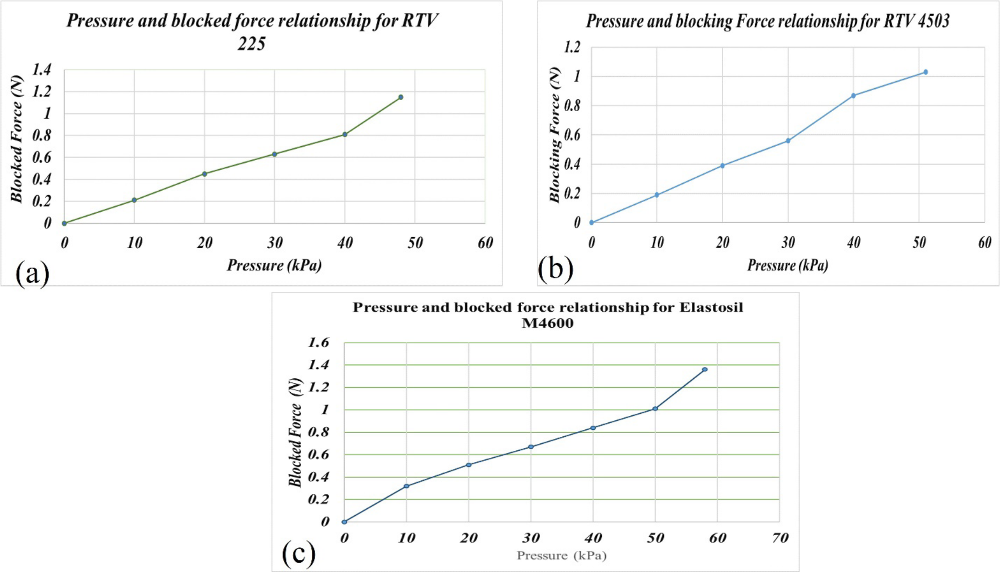

Fig. 7. Pressure and blocked force test for RTV 225, RTV 4503 and Elastosil M4600 fabricated actuators

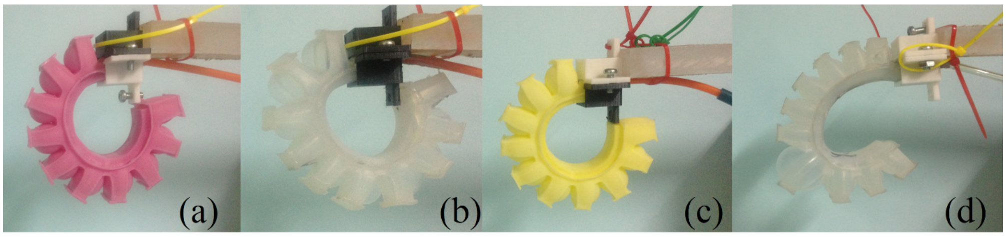

Fig. 8. setup for free travel trajectory tracking test: (a) Full bending for RTV 225 fabricated actuator, (b) Full bending for Elastosil M4600 fabricated actuator, (c) Full bending for RTV 4503 fabricated actuator, (d) Some of the Elastosil M4600 actuator shows extra inflation at some chamber.

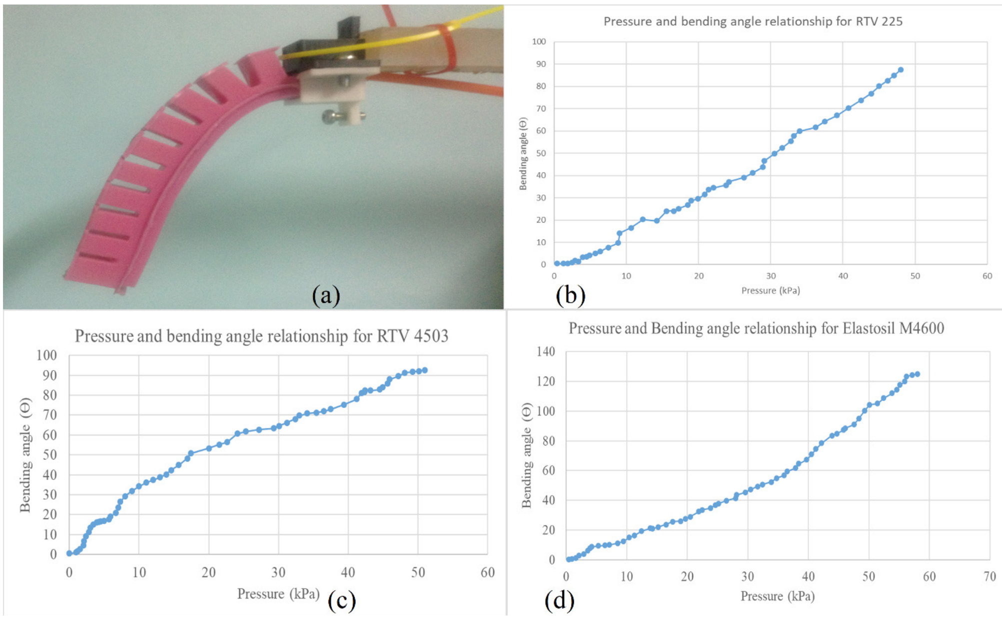

Fig. 9. setup for estimating bending angle variation with pressure: (a) Experimental setup and bending angle definition, (b) Pressure and bending angle for RTV 225, (c) Pressure and bending angle for RTV 4503, (d) Pressure and bending angle for Elastosil M4600.

cated actuator while RTV series fabricated actuators showed free travel bending of 59° and 53° for RTV 225 and RTV 4503 respectively. Higher free travel bending of RTV series actuators were observed and it can be explained by the lower stiffness of materials.

The soft robotic actuators were pressurized until the full bending at constant pressure as shown in figure 8 and deformation was recorded by high resolution camera (iSight camera, iPhone 5) then bending angle was analyzed with tracker (https://physlets.

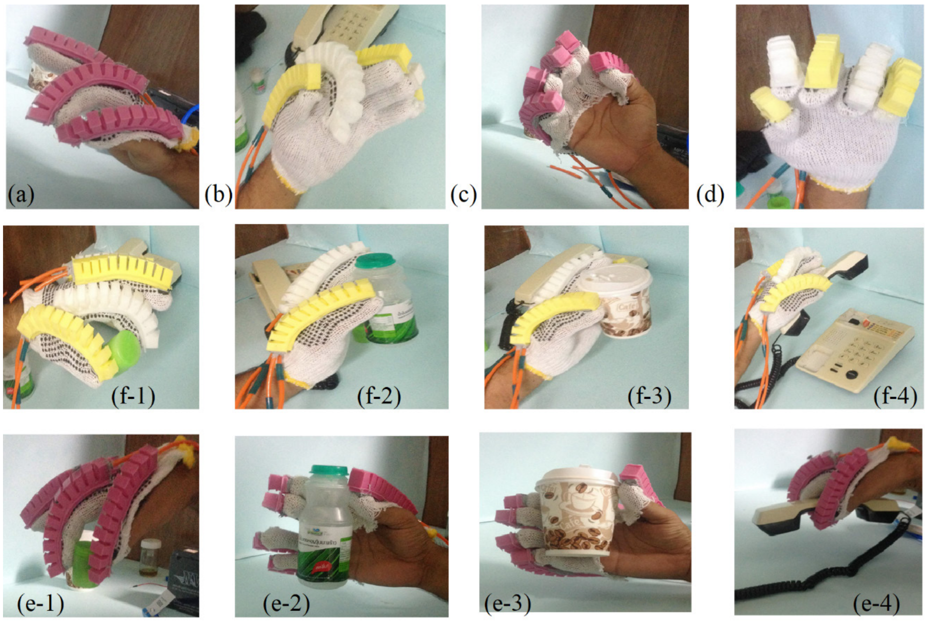

Fig. 10. Grasping ability test for soft robotic glove: (a) Pinching pose with thumb and index finger (RTV 225) (b) Index finger bending (RTV 4503) (c) Full hand flexion with robotic glove (RTV 225) (d) Full hand flexion with robotic glove (RTV 4503) (f-1, e-1) Grasping a small bottle with pinching posture (f-2, e-2) Grasping ability of small water bottle with full hand (f-3, e-3) Grasping ability of robotic glove for coffee cup (f-4, e-4) picking up the telephone receiver without small finger actuated.

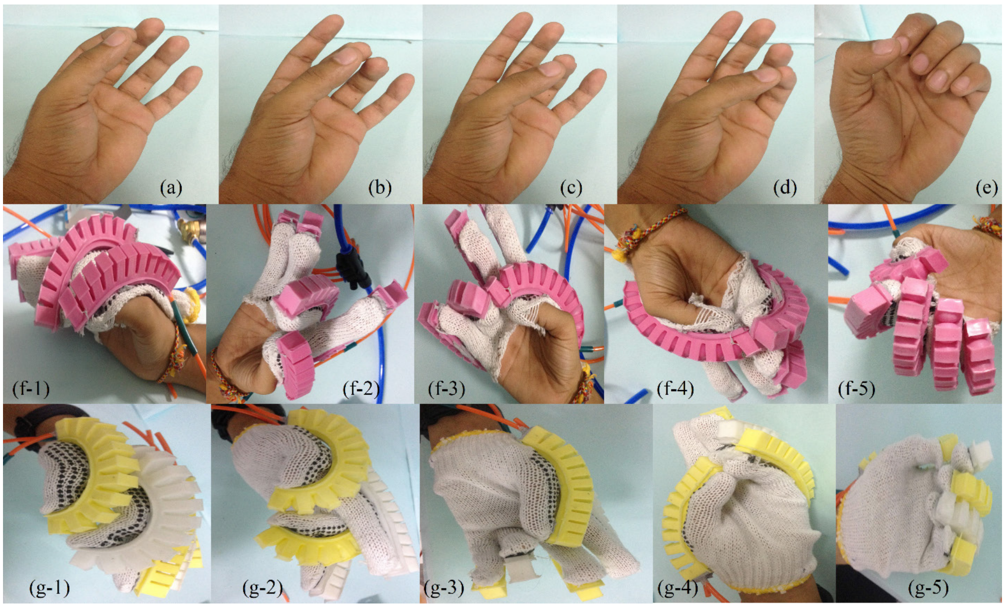

Fig. 11. Kapandji test for rehabilitation purpose: (a) thumb contact with index finger (b) thumb contact with middle finger (c) thumb contact with ring finger (d) thumb contact with small finger (e) full hand flexion (f-1 – f-4) soft robotic glove assembled with RTV 225 performing all above posture (g-1 – g-4) robotic glove performing the human hand posture for rehabilitation standardized test.

org/tracker/). The experimental results of free travel trajectory over input pressure is shown in figure 9. The definition of free travel trajectory (bending angle) is defined in figure 9a. The relationship of free travel trajectory and input pressure is almost linear. Initial angle was deducted and then response was plotted as shown in figure 9(b), 9(c) and 9(d).

All three soft robotic fingers were tested for deflection angle while going under grasping process. RTV 225 fabricated soft finger shows the 87° deflection at 48 kPa while RTV 4503 fabricated finger shows the deflection of 92° bending deflection under 51 kPa and Elastosil M4600 fabricated finger goes under the deflection of 124° bending deflection when 58 kPa pressure is applied. While testing the Elastosil M4600 fabricated finger, it has been observed that some finger shows extra inflation (from desired).

4.3. Grasping Ability

Grasping ability of Pneumatic robotic glove was tested with healthy subject wearing the glove. Soft robotic glove consisted of a woven glove on which pneumatic actuators were glued gives the maximum comfort to user's hand. The total weights are 157.82 g and 160.17g respectively for gloves assembled with actuators fabricated of RTV 225 and RTV 4503. The ideal soft robotic hand should not exceed from 0.5 kg [67]. Glove can be easily mounted and dismounted as it fits the human hand easily.

The healthy subject was instructed to relax his muscles and air pressure was inserted in pneumatic actuators to assist the hand for grasping the objects as shown in figure 10.

4.4. Kapandji Test

Finger opposition using thumb is one of the more difficult exercise for people having grasping difficulties. There are some standardized tests to evaluate the ability of affected hand where Kapandji test [66] is one of these test which implemented on healthy subject. Figure 11 shows the hand postures for standardize Kapandji test and hand flexion.

5. Discussion and Conclusion

In this paper, wearable soft robotic gloves design, fabrication and testing has been presented. Pneumatic actuators were designed and fabricated with three different materials. These actuators are one of the best alternatives for rigid and fixed actuators being used in rehabilitation devices. Results shows that glove have capability to replicate the rigid and fixed devices for rehabilitation exercise and can help for daily living activities and rehabilitative exercises.

Pneumatic actuators were designed base on PneuNets architecture. The selected geometry was printed with 3D printer and fabricated using three different low cost soft silicon materials with high elongation properties. Actuation pressure was measured with pressure sensor while actuation speed and bending angle was measured using Tracker. Some of the Pneumatic actuators fabricated with Elastosil M4600 shows extra inflation in some chamber upon pressurizing above from 30kPa which can affects the bending of robotic glove. Due to unwanted inflation, Elastosil M4600 fabricated actuators were not chosen for assembling the soft robotic glove. Different mixing ratios were experimented to find the desired curing time and stiffness for RTV 4503 and RTV 225 silicones. Gloves assembled with RTV series silicones shows reliable grasping and continuous flexion and extension of human hand.

Rehabilitation device for hand should not be more than 0.5 kg as a standard for getting the better result for rehabilitation where robotic gloves proposed in this work weighs 157g and 160g as compared to 220g [73] and 230g [74-75]. A rehabilitation finger should generate block force of 1N magnitude to facilitate the rehabilitation process. Results shows that robotic finger fabricated with these low cost silicones generate more than 1N. Results shows the human hand flexion, extension with one of the standardized rehabilitation test and grasping of daily living activities object.

By comparing the test results and observations, robotic glove assembled with RTV 225 silicon actuators shows more reliable grasping and fast rehabilitation exercise movements as compared to robotic glove assembled with RTV 4503 silicone actuator. Currently soft robotic gloves are pressurized with single input air source with open loop strategy. All the actuators are being actuators with single air source resulting uniform air pressure to all actuated. Introducing different sensors with close loop strategy can lead toward the better control and reliable actuation.

There were some observations made during the testing of pneumatic actuators.

- Increasing the curing agent can lead to higher stiffness, higher pressure, durability, and lower curing time.
- It has been observed that direct stirring causes a large number of air bubbles inside the mixed solution for which higher vacuum inside the chamber needed to remove the air bubbles. Trying different mixing method can reduce the air bubble production inside the solution.
- Block force magnitude can be increased by increasing the hardness of materials which result in bearing higher pressure to generate higher force.
- It has been observed that some actuator fabricated with Elastosil M4600 shows extra inflation at some chamber which make it inadequate where full bending of actuator is required.

This paper presents low cost soft robotic glove with open loop control strategy for assisting at-home rehabilitation and daily living activities. Soft robotic gloves presented in this paper are assembled with pneumatic actuators fabricated with low cost silicones (RTV 225 and RTV 4503). These actuators show the fast response on low pressure [76]. Experimental results show the ability of grasping and rehabilitation test with passive healthy human hand. The proposed robotic glove with low cost material exhibits the potential for low cost solution of human hand rehabilitation. In future, closed loop strategy with feedback from different sensors like force sensor and elastic joint angle sensor can lead to better performance of these gloves. Furthermore, increasing the material stiffness with different curing agent ratio can lead the actuators to withhold higher pressure.

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