A Wearable Soft Robotic Glove for Rehabilitation of Paralyzed Hand

Amir Souhail

A Thesis Submitted in Fulfillment of the Requirements for the
Degree of Master of Engineering in Mechanical Engineering
Prince of Songkla University
2019

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Author	Mr. Amir Souhail
Major Program	Mechanical Engineering

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I hereby certify that this work has not been accepted in substance for any degree, and is not being currently submitted in candidature for any degree.

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Abstract

Stroke attacks are the one of major reason in hindering the human hand functionality and cause disability. Soft robotic is playing a major role in rehabilitation where different robotic gloves are being developed. Due to light weight, portability and safe human-robot interaction, soft robots are best alternative of rigid robots. Soft pneumatic actuators were designed and fabricated with three different silicon materials. Silicone materials were chosen because of low cost and locally availability. Three different materials for fabrication are RTV 225, RTV 4503 and Elastosil M4600. Tensile tests were done on each material specimens for material properties. Uniaxial tensile test tests were done with speed of 100 mm/sec on Zwick 10 testing machine with dog bone specimen. Elastosil M4600 shows the highest elongation (700%), tensile strength and modulus while RTV 225 shows the medium elongation (500%), tensile strength and modules. RTV 4503 shows the lowest elongation (200%), tensile strength and modulus. Actuators were tested for blocked force generation, actuation speed, bending angle, bending time and full bending pressure. Soft actuators showed the initial bending due to softness and gravity. Elastosil M4600 actuator showed the initial bending of 49° while RTV 225 and RTV 4503 shows 59° and 53° respectively. Elastosil M4600 achieved full bending at 58kPa while RTV 225 and RTV 4503 achieved full bending at 48kPa and 51 kPa respectively. RTV 225 showed the fast response as compared to two other actuators. Elastosil M4600 actuator shows the block force of 1.36 N, RTV 225 shows 1.13N and RTV 4503 shows 1.03 N at full bending pressure. Elastosil M4600 actuators shows the highest bending angle of 166° at full bending where RTV 4503 have bending angle of 143° at full bending while RTV 225 have bending angle of 144° while achieved the full bending. Three soft robotic grippers were assembled. 3D printed connector and base were used to assembled the soft grippers. Different objects having different shapes, sizes and weights were chosen to test the ability of soft robotic grippers. Result shows the reliable grasping of objects. Soft robotic gloves were assembled and tested for daily living activities and rehabilitation purpose. Four different objects were chosen to test the grasping ability of soft robotic glove. Kapandji test was done with RTV series actuators to validate the postures of rehabilitation test. Tests were done on healthy object. Result shows the reliable grasping and rehabilitation exercise.

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I would like to thank my advisor Asst. Prof. Dr. Passakorn Vessakosol for his continuous availability, leadership, encouragement throughout my study. I would also like to thank him for providing me full support and insightful thoughts throughout my studies period. I am also very thankful to Assoc. Prof. Dr. Pruittikorn Smithmaitrie and Assoc. Prof. Dr. Wiriya Thongruang for joining the thesis examination committee.

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Amir Souhail

Contents

List of papers/proceedings

1. Amir Souhail and Passakorn Vessakosol, "**PneuNets Bending Actuator Design and Fabrication Using Low Cost Silicones**," in The 9th TSME International Conference on Mechanical Engineering, 2018 (**Manuscript Accepted**).
2. Amir Souhail, Passakorn Vessakosol (2018). **Low Cost Soft Robotic Grippers For Reliable Grasping**. Journal of Mechanical Engineering Research & Developments, 41(4):88-95
3. Amir Souhail and Passakorn Vessakosol, "**Low Cost Soft Robotic Gloves for at-Home Rehabilitation and Daily Living Activities**" submitted to be published in Topics in Stroke Rehabilitation (ISSN: 1074-9357, 1945-5119)

Preface

With increasing population of world, number of stroke patients are also increasing. Fifteen million people around the world experience the stroke attack annually and this number is expected to increase with time. Different repetitive exercises are designed for rehabilitation of affected part. Human hand is one of the important part in daily living activities and its disability cause other health problem like depression etc. Different rehabilitation exercises were designed to regain the muscle strength. Different robotic devices were designed for repetitive rehabilitation exercises which shows the more improvement in rehabilitation as compared to manual rehabilitation done by therapist.

A number of robotic devices were designed for rehabilitation which consist on rigid material like motors, gear and screws etc. These robotic devices are rigid, fixed and difficult of align with biological joint of human hand. These devices are mostly designed for clinical setup and not suitable for assisting in daily living activities. In last decade, new emerging devices were designed and tested with development of new materials which are being used in soft robotic devices for rehabilitation. In recent times, soft robotic devices show the promising replacement of rigid exoskeletons for rehabilitation and leading towards the comfortable, safe human-machine interaction and lightweight devices.

The aim of this work to develop a prototype of soft robotic gloves for rehabilitation of human hand. Main objectives of this study are

1. Design and fabrication of soft pneumatic actuator
2. Study different suitable material for fabrication of soft pneumatic actuator
3. Assemble soft pneumatic actuator for soft robotic gripper and soft robotic glove for rehabilitation of stroke patients.

these objective was fulfilled in different stages throughout the research. Different robotic devices and actuation methods were studied in first stage. By comparison, soft robotic glove and pneumatic actuation method was chosen due to their low weight and safe human-machine interaction. Soft pneumatic actuators were designed and printed with 3D printer. Design and dimension are presented in Appendix A and B. Finite element methods (FEM) were performed for pneumatic actuator which allows us to see the behavior of pneumatic actuator before printing the molds to fabricate the actuators. Elastosil M4601 were chosen material to model the actuator because it has almost same material properties as our materials. Based on Finite element method analysis for different chamber height, wall thickness and distance between chambers, this geometry was chosen as it shows the desired behavior of pneumatic actuators. Due to nonlinear behavior of hyperplastic materials, it’s difficult to find the accurate coefficient for different hyperplastic models. Deformation analysis result and Ogden model coefficient values for RTV 225 is shown in Appendix D. These coefficients were found with Hyperfit and MCalibration software’s.

After that, 3 different silicone material (Elastosil M4600, RTV 225 and RTV 4503) were chosen because of low cost, locally availability and matching properties as found in previous literature. Theses material consist on two part where part A is flow-able silicones while part B is curing agent. Elastosil M4600 have two parts while in RTV series, paraffin oil was added to reduce to concentration of part A. the material was directly stirred and mixed solution was prepared. Mixture were poured directly into 3D printed molds. Mixed solution have air bubbles because of direct mixing of parts which was removed with vacuum air chamber. All three materials are room temperature cured silicones so molds took 8-10 hours to get fully cured. Fabricated actuators are presented in Appendix A, Appendix B and Appendix C.

Different mechanical properties of these materials were measured with uniaxial tension test. Modulus, tensile strength and elongation of these materials were measured. Single actuator was tested fabricated with all three materials. Actuation speed, bending angle and time relationship, bending angle and force relationship and blocked force generated at tip was measured. Elastosil M4600 shows higher tensile strength, elongation and modulus while RTV 225 have medium tensile strength, elongation and modulus and RTV 4503 shows the least values of these parameters. Mechanical properties of these material is presented in Appendix B. In last stage, two applications were assembled with fabricated soft pneumatic actuators which are soft robotic gripper and soft robotic glove for rehabilitation. For soft robotic gripper, connectors were designed and 3D printed to connect the actuators with base. Three actuators were choose considering the human hand ability to pick an object reliably. Different object with various weights, radius and weights were chosen to test the ability of gripper. The details of design, assembly and result is presented in Appendix B.

Soft robotic gloves were assembled with woven glove and soft pneumatic actuators. Each actuator was glued starting for the tip of woven glove resulting in different reference point for each finger. Control system for soft robotic grippers and soft robotic gloves consisted on low cost air pump, solenoid valve, pressure sensor, manifold and power supplies. Soft robotic grippers and gloves were operated with open loop control strategy. Soft robotic gloves were tested with healthy object. Four different objects (Small bottle, telephone receiver, small water bottle, coffee cup) were chosen where different kind of hand postures were required. Different postures of human hand were also performed to validate the flexions and extension. For rehabilitation purpose, Kapandaji test postures were tested with healthy object which involve thumb interaction with each finger and considered as one of the difficult test in rehabilitation practices. The details of assembly and result is presented in Appendix C.

In future work, closed loop control strategy with different sensor (Elastic joint sensor, force sensor, EMG’s sensor, Brain computer interface) can be implemented. Further development in control system which requires high quality air supply, independent low weight power supplies and independent supply to each robotic finger will improve the performance of system.

Grasping force and reliable contact with object can be increased by increasing the actuator’s surface friction. Paraffin oil used for reducing the concentration of part A can be varied to increase the fraction which can lead to more reliable grasping. Actuators stiffness can be increased by increasing the curing agent while achieving the right viscosity and curing agent. For soft robotic grippers, different number of actuators can be attached with base with different kind of objects. It can be varied from 2 to 4 actuators to study the relation of grasping with object shape and weight. Future work can also include the natural rubber materials because of their higher elongation and ability to withstand with higher pressure.

Different soft pneumatic actuators presented in literature show the stability of actuator ever than 1 million cycle. Although these experiment were conducted under the moderate strain levels. In future work, performance of pneumatic actuators fabricated with RTV series and Elastosil M4600 can be evaluated with different applied strain levels.

Currently we conducted the glove test on healthy object while instructed to keep his muscles in relaxed form. In future, test can be conducted on stroke effected patient to observe the rehabilitation speed. Designing Base pad for robotic glove can also be a future work which can replace the woven glove for better performance. This prototype can be installed at rehabilitation center and at home after testing with multiple stroke effected patients.

The outcome of this research provides the new low cost soft materials for soft robotics and low cost solution for rehabilitation devices and small industrial grippers.

Appendix A

Souhail A, Vessakosol P. PneuNets Bending Actuator Design and Fabrication Using Low Cost Silicones. In: The 9th TSME International Conference on Mechanical Engineering. Phuket, Thailand; 2018:1-7.

PneuNets Bending Actuator Design and Fabrication Using Low Cost Silicones

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Abstract Advances in soft materials, material science and rapid prototyping is playing the key role in rapid development and improvement of soft robotic rehabilitation devices. This article presents a pneumatically actuated soft robotic glove fabricated with combination of low cost silicon (RTV 225), Silicon (RTV4305), Elastosil M4600 and an inextensible material. Pneumatic pressure is responsible for flexing and extending of actuator. Soft material and pneumatic actuation make the human-machine interaction safer and increase the user's freedom.

1. Introduction

Unlike traditional rigid body robot, soft robots use their flexibility to achieve certain tasks that rigid body robots can't. Among soft robotics structures, soft robotic actuators have been cornerstone of soft robotics since its recent beginning. Different actuation approaches are being reported in literature which include shape memory alloys actuator (SMA's)[1-2], cable driven actuator [3], pneumatic actuators[4-5-6], fluidic actuator[4], vacuum driven actuators[5] and chemical reaction driven actuator[9-10].

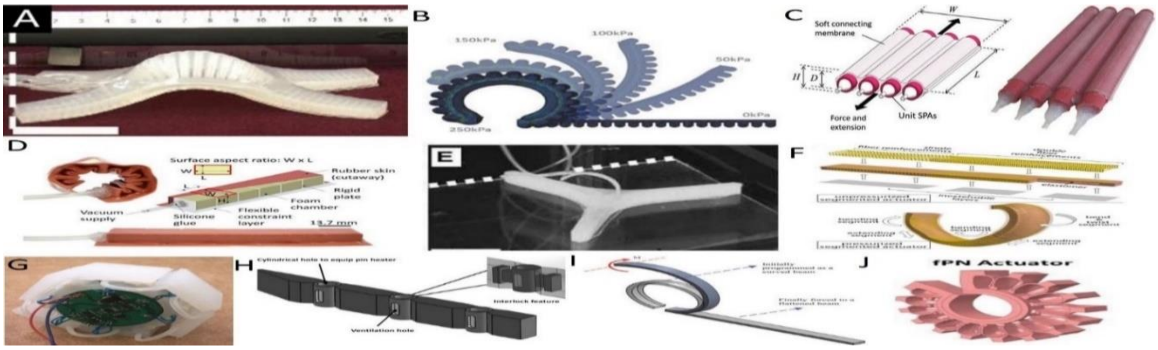

Figure 1. Soft Robots with different actuation methods (A) PneuNets actuator based soft robot[8] (B) Single channel pneumatic actuator [9] (C) Soft pneumatic actuator pack muscle actuator[10] (D) Vacuum actuated soft actuator [5] (E) Explosive based jumper soft robot [7] (F) Fluid pressurized soft robotic actuator [4] (G) On – board chemical reaction based soft robot [6] (H, I) Shape memory alloy actuator[1-2] (J) PneuNets actuator [12].

Soft pneumatic actuator is a hotspot research area due to softness, lightweight, safe human machine interaction and low fabrication cost. Many research groups have developed different types of pneumatic actuators that are being used in different application from industrial hand for grasping to soft robotic rehabilitation glove [13-14-15-16-17].

Different studies show that material properties affect the bending of soft pneumatic actuator (SPA). Materials with lower elongation moves slower as compared to material with higher elongation [14]. Due to nonlinear behaviour of silicon elastomers and complex geometry of actuator, it's difficult to predict the accurate behaviour of actuator. Some of the reported materials in literature are Eco-flex 30[15], Elastosil M4601[16] ,Sylgard 184 [12], KE-1300 and KE-1300T [21-22] .

In this paper, we present PneuNets actuator with low cost and locally available material. The design structure is modified from Soft Robotic Toolkit [18]. Elastosil M4600, RTV 225 and RTV 4503 is being used in fabrication of SPA's. Blocked force test, actuation speed and payload capacity characteristics are being assessed in real situation. In the end, we present the conclusion of this paper in section 5.

2. Design

Soft robotics is highly inspired from nature that gives us the clues about designing of actuators. As human hand is one of the best grippers found in nature so pneumatic actuator is inspired modelling a human finger (Figure 2). Pneumatic actuator is designed to flex and extend as human finger. It consists of silicon chamber as square body that is attached with inextensible layer and base.

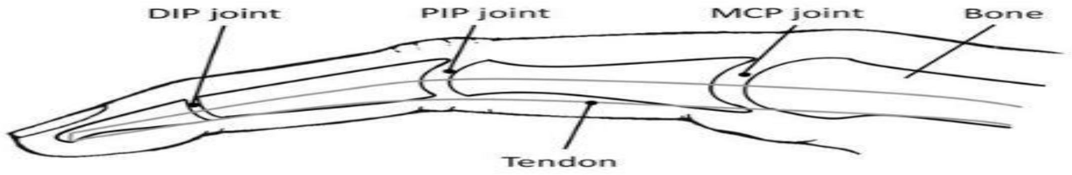

Figure 2. Anatomic sketch of the human index finger [11]

When pneumatic pressure is applied on internal walls of actuator, chambers start expanding and walls of chamber bulge out most. This causes the actuator to move in axial direction. To prevent the axial movement, strain limiting layer (Paper) is used which makes the actuator start bending. Figure 3 shows an overview of the process.

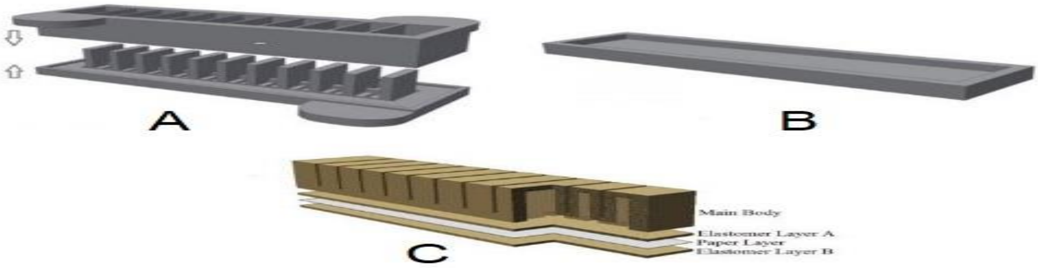

Figure 3. Overview of design process [18] (A) Two part mold for air chamber (B) Base mold for sealing the air chamber (C) actuator design parts.

3. Fabrication

Pneumatic actuator is fabricated with Elastosil M4601 (WACKER CHEMIE AG, Germany), RTV 225 (GGC, Taiwan) and RTV 4503 (GGC, Germany) due to low cost, availability and comparatively similar properties as different silicon elastomers reported in previous work. Elastosil M4600 have the pre-determined fixed mixing ratio while RTV255 and RTV 4503 do not have fixed ratio and can be adjusted as per the required stiffness, viscosity and curing time.

Table 1. Properties of silicon used in fabrication process

Properties	Silicon (RTV 225)	Silicon (RTV4503)	Elastosil M4600
Tensile strength ($\boldsymbol{N/mm^2}$)	≥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/mm^2)	≥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/cm^3)	-	Approximately 1.16	1.1
Density at 23° in water ($\boldsymbol{g/cm^3}$)	-	1.16	1.1
Elongation at break (%)	≥420	400	800

Silicon RTV 225 and RTV 4503 have adjustable part A and Part B where Paraffin oil was used to control the concentration level of part A. Like most of the silicon elastomers, RTV 225 and RTV 4503 have also two parts. Part 'A' is flowable liquid while part B is curing agent. For finding the right mixing portion to have an optimum desired stiffness for actuator, we used different mixing ratios of part 'A', paraffin oil, and part 'B' (curing agent).

Table 2. Mixing ratios of RTV 4503 Silicon elastomer

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	8.68	1.81
89.05	9.56	1.39
90.01	8.81	1.18

Table 3. Mixing ratios of RTV 225 Silicone 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
88.90	9.62	1.48
89.12	9.42	1.46
88.56	10.03	1.41

89.11	9.52	1.37
89.96	8.52	1.16
89.67	9.32	1.01

These three elastomers are operated to be cured at room temperature. Part ‘A’ and ‘B’ of Elastosil M4600, and RTV 225 and 4503 Part ‘A’, part ‘B’ paraffin oil was stirred through electric mixer (stand mixer EMS-52, distributor: TCE Co., Ltd., Thailand) properly for 1-2 minutes. Stirred mixing generate the air bubbles in silicon mixture that make it not suitable for pneumatic actuator. This is because excessive air bubbles in the elastomer surface may cause the material failure upon the inflation (inlet pumping air in our case) stage. To resolve this, a custom-made vacuum air chamber was used. A vacuum pump (PVL35 Genvac, general vacuum & flow Co.,Ltd, Thailand) took out the air bubble from prepared mixture of silicone elastomer within 2-3 minutes after keeping it in the vacuum chamber.

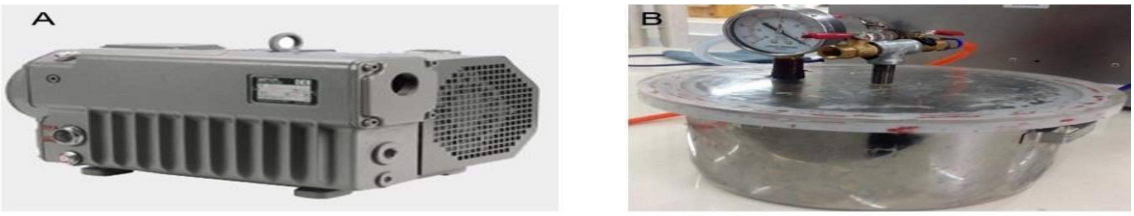

Figure 4. Setup for degassing from silicon mixture (A) PVL 35 Oil-lubricate Single Stage Rotary Vane Vacuum Pump [19] (B) Custom made vacuum chamber.

Mixed solution is directly poured into 3D printed mold of the pneumatic actuator. Figure 5 shows the 3D printed mold design and the pouring process.

Figure 5. Overview of fabrication process (A) 3D printed molds (B) pouring of silicon in air chamber mold (C) Sealing the air chamber with base mold (D) fabricated air chamber with air inlet.

4. Results

There are different significant characteristics that include the speed of actuation, bending angle and grasping ability. One end of the SPA’s was fixed.

Figure 6. Experimental set up.

Figure 7. Bending at 360 degree (A) Silicon RTV 4503 actuator full bending at 85 KPa (B) Silicon RV 225 actuator full bending at 75 KPa (C) Silicon Elastosil M4600 actuator full bending at 90 KPa.

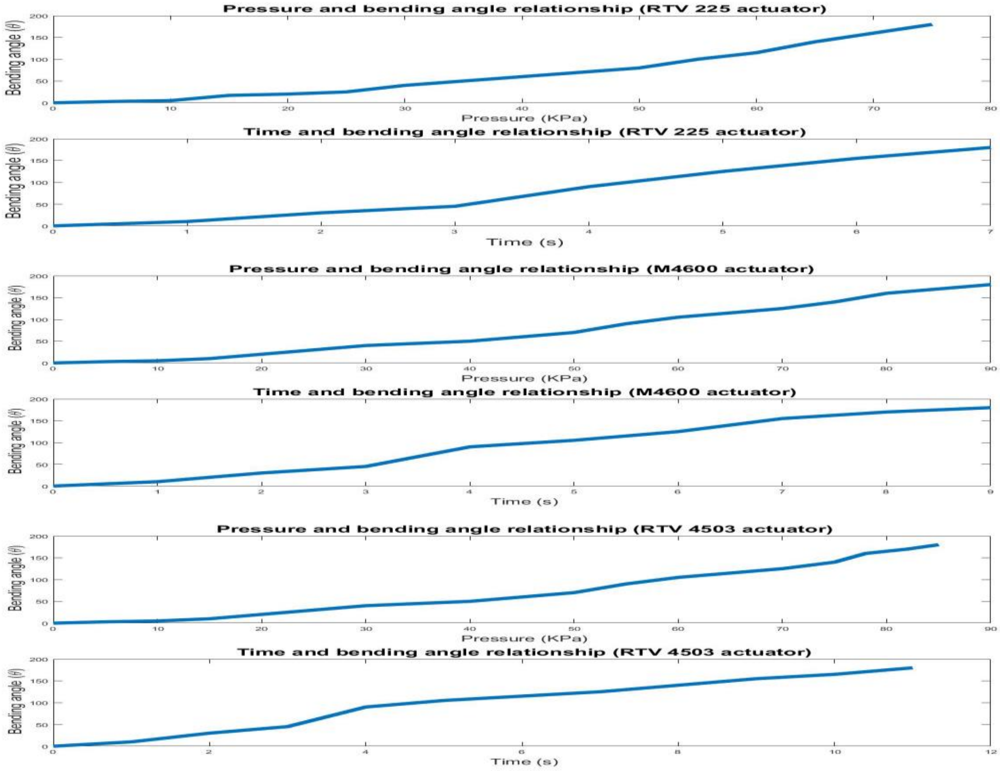

Figure 8. Time, pressure and bending angle relationship for Silicon RTV 4503, Elastosil M4600 and Silicon RTV 225.

Figure 9. Grasping different object with RTV 4503 actuator (A) circular bottle (B) circular pipe (C) rectangular shape.

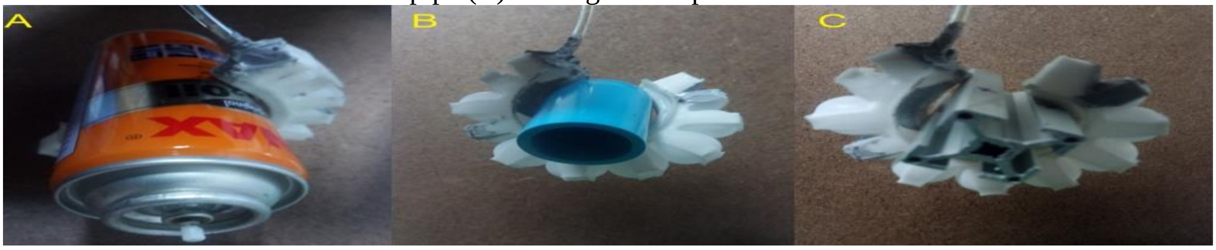

Figure 10. Grasping different objects with RTV 225 actuator (A) circular bottle (B) circular pipe (C) rectangular shape.

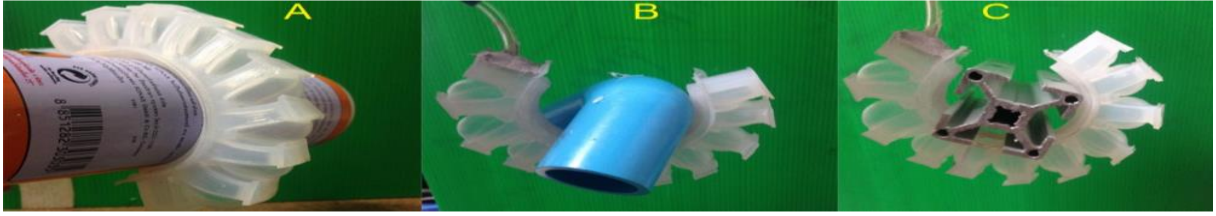

Figure 11. Grasping different objects with Elastosil M4600 actuator (A) circular bottle (B) circular pipe (C) rectangular shape.

5. Discussion and Conclusion

During the fabrication process, various stiffness levels were tested to obtain appropriate stiffness of soft actuators through fabrication. This was done by using different ratios of the curing agent that yielded different stiffness of the silicone mixture. For RTV 225 silicone elastomer, nine different mixing ratios were tried. In RTV 225, curing agent ratio from 1.41 to 1.16 shows the desired flowability and stiffness. By increasing or decreasing the values from this range, curing time, viscosity and stiffness can be controlled. It is critical to note that higher values of the curing agent will decrease the curing time and viscosity and vice versa. Whereas, for RTV 4503, almost double ratio of curing agent is required to get the optimum viscosity, curing time and stiffness. During its preparation, nine different mixing ratios were tried with curing agent ratio ranging from 2.45 to 1.99. This curing agent ratio range proves to be appropriate with suitable stiffness, viscosity and overall curing time.

Using the prepared mixtures of all three elastomers, three pneumatically actuated soft actuators were designed and fabricated. During the experiments, to achieve a full 180 degrees bending of all actuators, various pressure profiles were recorded. It was observed that all soft actuators tend to show proportional bending with respect to inlet pressure. RTV silicone elastomers made soft actuators exhibit more adaptive grip during the grasping experiments due to their consistent inflation. On the other hand, Elastosil made soft actuator showed similar grasping but tend to inflate higher (than desired) at some chambers due to minor uneven chambers. In overall, silicone elastomers proved to be more suitable for the development of a soft robotics manipulation structure such as a soft actuator. Further development requires accurately fabricated chambers that can distribute the pressure evenly upon inflation via inlet. Improving the fabrication quality along with testing the soft actuators in the combination of two and three simultaneously, would provide firm grasping of objects. This could further lead the research to be used in delicate object manipulation in a factory setting or its further development to use it as a human hand/finger rehabilitation device.

Finally, in this paper, mechanical properties of three different elastomers are reported. Using each, three pneumatically actuated soft structures are designed, fabricated and tested. Testing involved checking the bending of actuators by recording the inlet pressure and then testing the soft actuators to grasp various objects of different weight and size. By analysing the results, critical points are described which lead to improving the current work through further development before employing it for manipulation of delicate objects.

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Appendix B

Amir Souhail, Passakorn Vessakosol (2018). **Low Cost Soft Robotic Grippers For Reliable Grasping**. Journal of Mechanical Engineering Research & Developments, 41(4):88-95

Low Cost Soft Robotic Grippers For Reliable Grasping

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Abstract:

Soft robotic gripper shows valuable role in those tasks where robotic gripper came in contact with delicate objects. Comparison with rigid grippers, soft robotic gripper can grip/manipulate variety of target objects. This paper presents soft robotic actuators fabricated with three different low cost silicones. These robotic actuators show fast actuation at low operating pressure. Three soft robotic grippers were assembled and tested through different tests to compare their performance. Different objects were chosen to test the grasping ability of gripper. Grippers shows the ability to grasp objects from 80.99 g to 4.07g at 30-13 kPa. Results shows that robotic gripper assembled with RTV 225 and RTV 4503 silicone shows the more reliable gripping as compared to Elastosil M4600 silicone. This work shows that these low cost and fast actuation of low pressure grippers have great potential application in food industry, fruits industry and in daily life.

Keywords: Soft Pneumatic actuators, Low cost silicones, Soft robotic gripper, 3D printed connector

1. Introduction:

Recent developments in soft robotics intrigued the researchers from various fields of engineering, biology, chemistry and mechanics to develop materials and applications ranging from rehabilitation gloves [1-2], grippers and swimming robots [3] etc. Soft actuators fabricated with entirely soft materials [4-5] show promising ability of handling a range of object like apple, lemon, coffee mugs [6-7-8-9] and porous objects [10]. Self-healing materials [11-12] and multi material structures [13-14-15] have improved the abilities of these grippers as shown in figure 1.

The ability of soft robots predominantly depends on the performance of their actuators. There are different kind of actuators reported in literature which can be divided into two categories [4]: 1) Electrical responsive actuators like ionic polymer– metal composite (IPMC) actuators [26], shape memory alloys (SMA) [27-28-29], magnetic gel elastomers [30], electrorheological fluids (ERFs) [30-31]. 2) fluidic actuators like hydraulic [32], pneumatic (Vacuum [7], compressed air [33], water [2]) actuators. In soft robotics, use of first category actuators is limited due to high operating temperature [34-35], low efficiency [35], fabrication complexity, high cost, short lifetime, low response and low output force.

In soft robotics, pneumatic actuators are broadly being used by many researchers

[36]. They offer great flexibility, adaptability, low cost, lightweight and safe human – robotic interaction while delivering high mechanical outputs on low input energy [18]. Due to advances in material sciences and rapid prototyping, soft pneumatic actuators are being used in different fields ranging from industry [37], space applications to medical usage [38]. In literature, pneumatic actuators can be divided into 3 main categories according to their degree of freedom: 1) single dimensional which can do extension and expansion [39], 2) dual dimensional which can do bending motions [40], 3) three dimensional which can cause rotating and some complex movements [4].

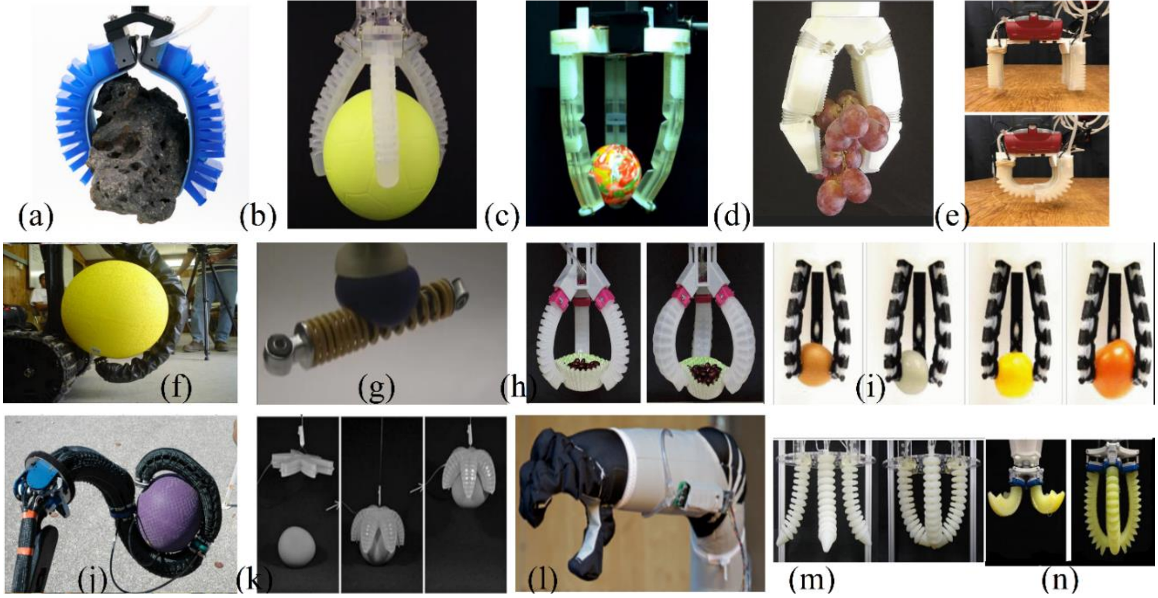


Figure 1. grasping and manipulation of delicate object is very hard to get with conventional robots while soft robotic gripper makes it simple: (a) Soft gripper with gecko-inspired adhesiveness [10], (b) Soft Somatosensitive gripper [16] , (c) Cable-Driven Soft Polymer gripper[17] , (d) Hybrid gripper [18] , (e) soft robotic gripper for neural networks [8] , (f, j) continuum manipulator [19] , (g) Gripper based on the particle jamming [20] , (h) Soft robotic glove for lunch box items manipulation [6] , (i)Multi material soft robotic gripper [21] , (k) Simple soft gripper fabricated by lithography [22] , (l) Inflatable robotic manipulator [23] , (m) Soft robotic arm gripper[24] , (n) Universal soft pneumatic gripper [25].

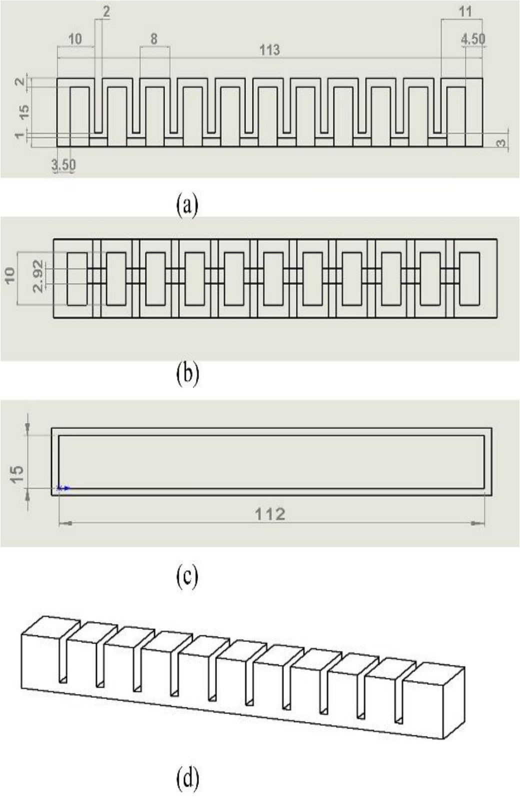
Soft pneumatic network actuators produce significant deflection on low pneumatic pressure and have considerable potential for medical application and soft grippers. These actuators use different soft material like Agilus 30 Black, VeroCyan [41], Dragon Skin 30 [42], Sylgard 184 [43], Smooth-Sil 950 [5], Ecoflex 00-30 [34], Elastosil M4601 [44-45], TangoBlackPlus, AR-G1L [6] and most of these material make its fabrication costly. In this work, locally available and low cast materials are explored to reduce the cost of actuator. Silicon RTV 225 and Silicon RTV 4503 along with Elastosil M4600 are used for fabrication of pneumatic actuators. Material test has been done to find the elongation and tensile strength of these materials. The objective of the proposed work is to explore low cost materials for soft robotics and soft robotic grippers for grasping variety of objects.

Section 2 describe the details about 3D designing of the actuator and connector for actuators which are used to assemble grippers. Section 3 elaborate the details about fabrication process of soft actuator and the assembly process of grippers. Section 4 describe about the testing setup for single actuator and for grippers. Section 5 describe the outcome of this work. Section 6 describe the conclusion of this work.

2. Design:

2.1. Actuator design:

The soft pneumatic actuator design is inspired and modified from PneuNets bending actuator [46]. Actuator have almost same dimensions as human finger. Actuator consists of 11 air chambers in which 9 have same length of 8mm while the end chambers have 10 and 11 mm wall thickness respectively. 1 mm height and 2.92 mm width air channel was designed for uniform air pressure on whole actuator. Geometry dimensions are shown in figure 2. A base was designed to enclose the air chamber. Geometry variation and its effects on the actuator performance are related parameters but this paper presents a detailed material properties evaluation and the overall actuator fabrication.



(a)

(b)

(c)

(d)

Figure 2. The Pneumatic actuator design's geometry: (a) The front view, (b) The bottom view, (c) Base for enclosing the air chambers, (d) diametric view.

To fabricate the actuator, required geometry was created with SolidWorks software. The molds and connectors were printed with Prusa I3 MK3 by using Polylactic acid (PLA).

2.2. Connector and base design:

As inspired from nature of our hand and it's grasping ability, three actuators were chosen by considering that this can produces minimum stable grasping. The cavity halves of both parts were according to the actuators dimension so that actuators can be fixed for stable grasping after screwing up together. The base design is simple square acrylic sheet which connects three actuators by drilling 4mm hole. The connectors were fixed with base by screws. The assembly parts are shown in figure 3.

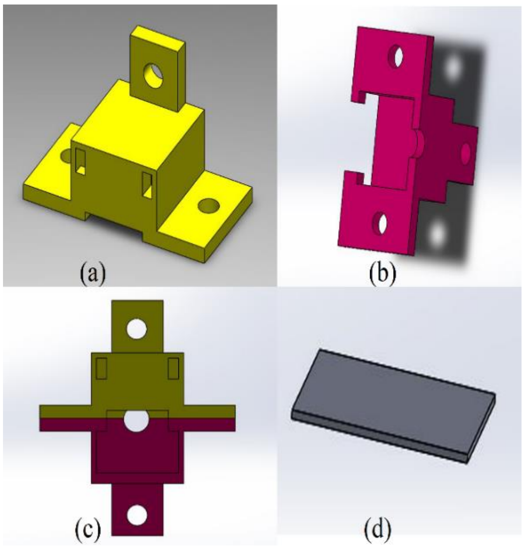


Figure 3. The connector and base components for gripper: a) the upper half, (b) The lower part, (c) Full view of connector after screwing upper half and lower half, D) A square acrylic sheet as base for connecting three actuators.

3. Fabrication:

Three materials were used to fabricate the actuators that are: 1) Elastosil M4600(WACKER CHEMIE AG, Germany). 2) RTV 225 (GGC, Taiwan). 3) RTV 4503 (GGC, Germany). Elastosil M4600 is room temperature cured material, however, curing time can be reduced by increasing temperature. RTV 225 and RTV 4503 is only room temperature curing silicones and heat cure does not affect the curing process. Elastosil M4600 have fixed mixing ratio of part A and part B by 10:1 while RTV 225 and RTV 4503 don't have fixed ratio for part A and part B. Part A is flow-able silicon while Part B is curing/oligomer/polymerization agent. Paraffin oil is added with RTV silicones for reducing the concentration level of Part A. To find the right stiffness and curing time, different mixing ratios were tested. Table 1 and table 2 Shows the different mixing ratios of silicon, paraffin oil and curing agent for RTV 225 and RTV 4503.

Table 1. Mixing ratios of RTV 4503 Silicon elastomer

Silicon (g)	Paraffin Oil (g)	Curing agent (g)
87.36	9.15	3.49
88.14	8.58	3.28
87.52	9.50	2.98
88.57	9.10	2.31
88.94	9.03	2.03
89.95	8.18	1.87

Table 2. Mixing ratios of RTV 225 Silicone elastomer

Silicon (g)	Paraffin Oil(g)	Curing agent (g)
88.34	9.53	2.13
89.56	8.80	1.64
89.12	9.42	1.46
89.03	9.56	1.41
89.96	8.52	1.16
89.62	9.32	1.06

A range of mixing ratios of silicones and curing agent were found which varies from 2.03-2.50 (g) for RTV 4503 and 1.06-1.50 (g) for RTV 225. Curing time for this range is 6-8 hours. Maximum elongation, average elongation, Tensile strength and modulus was found with tensile testing method.

The mixed solution was poured directly into 3D printed molds. First, upper and lower molds were fixed with clips to prevent leaking as viscosity of silicon is high. This mold is left for curing from 6-8 hours. Secondly, silicon mixed solution was poured into base mold. As we have to insert a paper layer as inextensible layer, small amount of silicon poured in base mold and left for curing. A paper layer inserted and more silicon is poured. Air chamber part was glued with base layer. The process to fabricate the air chamber, base and then enclosing the air chamber with base is shown in figure 4.

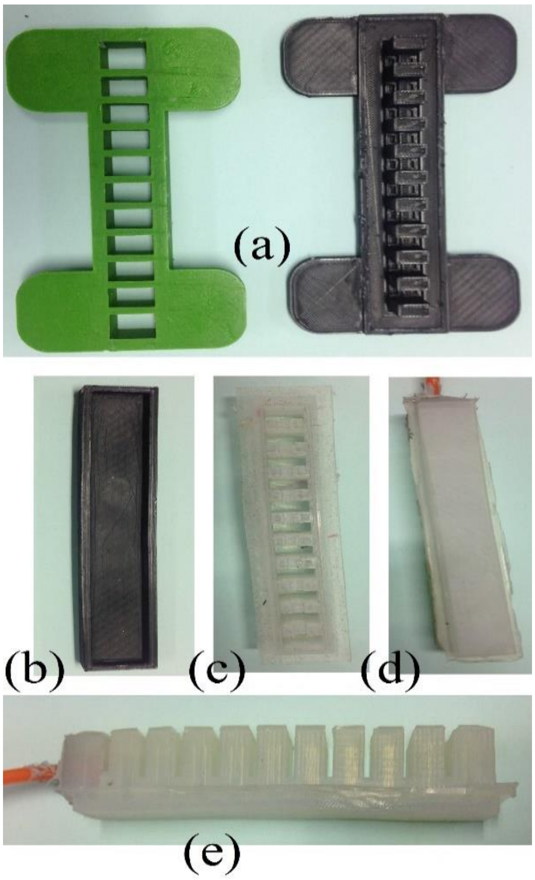


Figure 4. Fabrication process of pneumatic actuator: (a) 3D printed upper and lower molds, (b) Base mold, (c) Fabricated air chamber part, (d, e) Enclosed

air chamber with base and embedded paper layer.

In soft robotics, Bubbles reduce the quality of a soft structure by making it uneven and cause leakage. After preparing the solution, it was degassed by using a custom made vacuum air chamber. The remaining bubbles were burst out with needle.

Three actuators of each material type has been inserted in3D printed connecter and screwed and then to base with screws. The gripper assembly process is shown in figure 5.

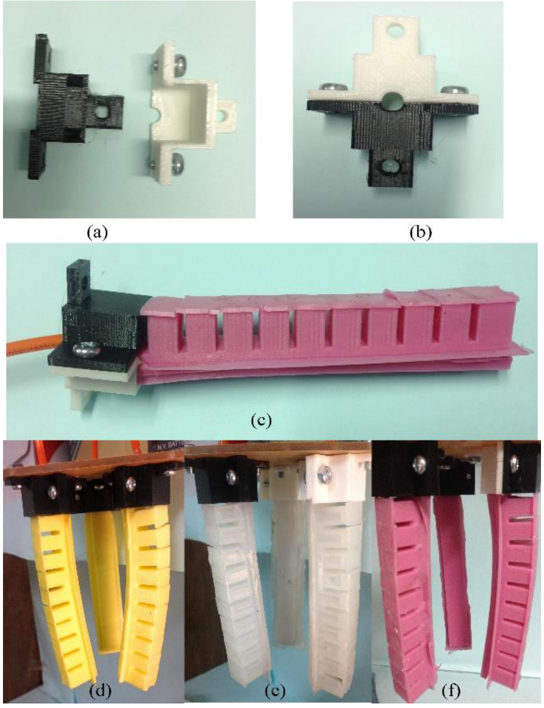


Figure 5. Gripper assembly process: (a) 3D printed connecter in two parts, (b) Upper and lower parts are screwed together, (c) Pneumatic actuator inserted in connecter, (d, e, f) Three actuators are connected to base with screws.

4. Results:

For performing single actuator testing and grasping testing, a small air pump was used to supply constant air supply with solenoid valve and pressure sensor (ASDXAVX100PGAA5) for monitoring the bending pressure and grasping pressures.

4.1. Mechanical properties test:

ASTM D412 standard [47] was used for testing the material properties of Elastosil M4600, RTV 225 and RTV 4305. A 3D printed mold was prepared to fabricate a sheet of 3mm thickness and then cut the dog bone sample with pneumatic sample cutter. Then uniaxial tensile test was conducted on these dog bone specimens. Tensile test was conducted using Zwick Z010 testing machine equipped with 100 N cell. These tests were conducted on speed of 100 mm/minutes till specimen break point as shown in figure 6(j, k, l). Five specimens of each material sheet were tested for tensile properties. Uniaxial tensile Testing process is shown in figure 6.

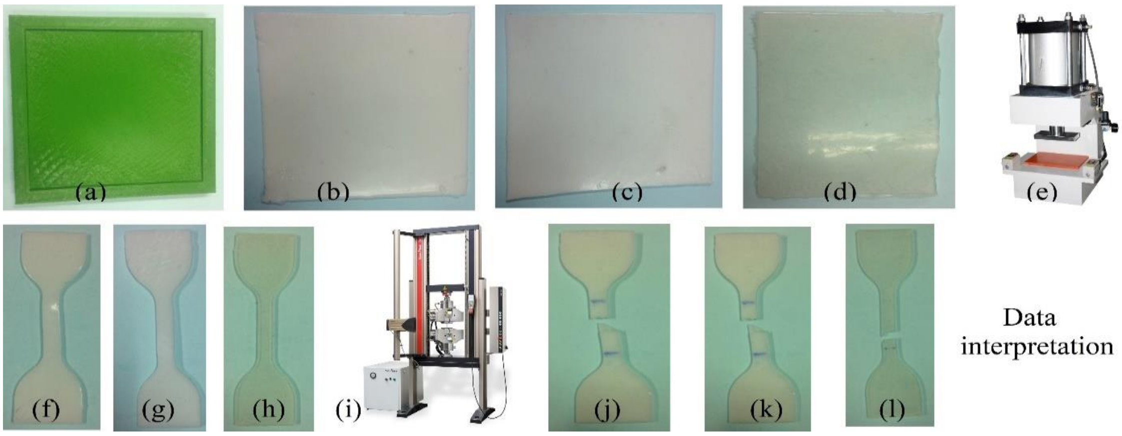


Figure 6. Tensile testing process: (a) 3D printed mold to prepare sheet, (b) RV 225 Sheet, (c) RTV 4503 Sheet, (d) Elastosil M4600 sheet, (e) Pneumatic sample cutter, (f, g, h) Dumbbell

specimen for RV 225, RV 4503 and Elastosil M4600 prepared according to ASTM D412, (Die C) Dimensions, (i) Zwick Z010 testing machine, (j, k, l) Dumbbell specimen tested till breaking point.

Different properties of three materials has been explored in this test which are elongation percentage, Modulus (100%,300%,500%) and tensile strength. Elastosil M4600 and RTV 225 shows the higher values of these properties as compared to RTV 4503. Figure 7 shows the graph of different properties.

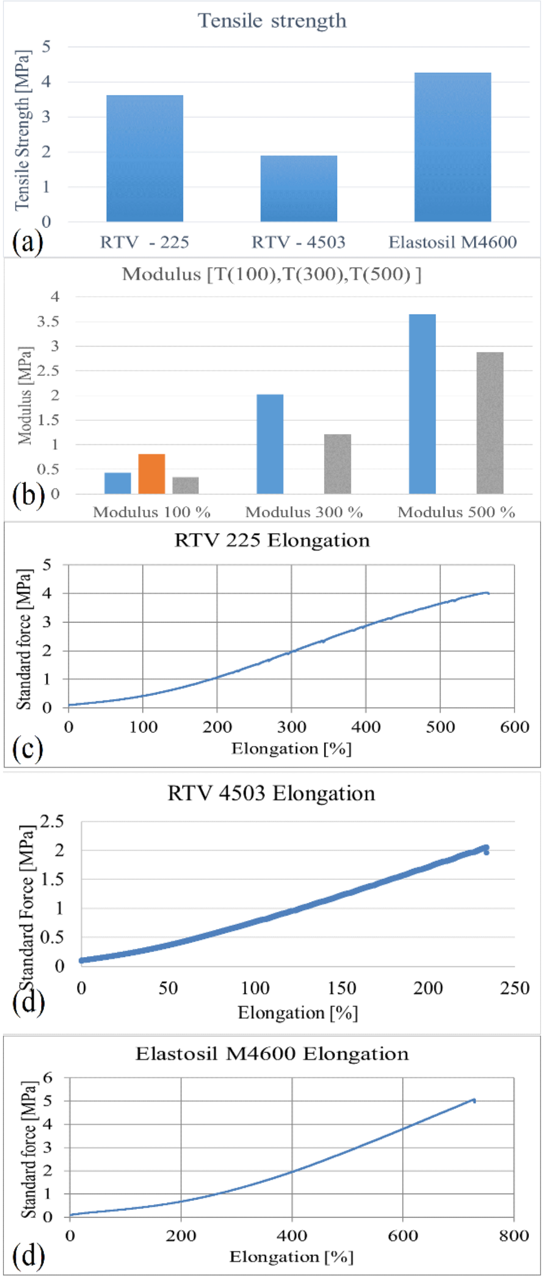


Figure 7. Uniaxial Tensile strength test for RTV 225 (polymerization/curing agent 1.31 (g)), RTV 4503(polymerization/curing agent 2.61 (g)) and Elastosil M4600: (a) Tensile strength, (b) 100 %, 300 % and 500 % modulus, (c) Maximum elongation for RTV 225, (d) Maximum elongation for RTV 4503, (e) Maximum Elongation for Elastosil M4600.

4.2. Single actuator test:

Single actuators fabricated from three different materials ware tested under different pressure until the full bending. Actuators has the initial bending because of gravity on soft bodies. Among those actuators, Elastosil M4600 fabricated actuator have least bending angle of 49° at 0kPa due to its higher shore hardness as compared to RTV 225 and RTV 4503.RTV 225 and RTV 4503 actuators have bending angle of 59° and 53° respectively at 0kPa as shown in figure 8 (a-1, b-1, c-1).

Actuators were fixed on one end and different pressure applied on every actuator until the full bending. Initially, pressure started from 10kPa and then increased with steps of 10kPa. Pressure was applied until the full bending. Definition of angle is showed in figure 8 (b-1). Due to higher shore hardness, Elastosil M4600 have slightly high input pressure as compared to RTV series silicones.

Bending angle and actuators response were analyzed with Tracker (https://physlets.org/tracker/). The relationship between time and bending angle is shown in figure 9.

Elastosil M4600 takes little longer time to achieve full bending as compared to RTV series silicones. It can be described by the shore hardness as part of material properties. The bending of each actuator at different pressure is shown in figure 8.

Figure 8. **experimental results of single actuator under different air pressure:** (a) full bending of actuator fabricated with RTV 4503, (b) full bending of actuator fabricated with RTV 225 , (c) full bending of actuator fabricated with Elastosil M4600, (a-1, b-1, c-1) actuators at 0 kPa (Initial position) , (a-2, b-2, c-2) actuators at 10kPa , (a-3, b-3, c-3) actuators at 20kPa, (a-4, b-4, c-4) actuators at 30kPa, (a-5, b-5, c-5) actuators at 40kPa (a-6) actuator fabricated with RTV 4503 bending at 51kPa, (b-6) actuator fabricated with RTV 225 bending at 48kPa, (c-6) actuator fabricated with Elastosil M4600 bending at 58kPa.

4.3. Objects grasping test:

For grasping test of gripper, different object with different shapes and weight were selected. It includes objects from daily life like tissue paper packet, a sponge foam, paper holder, water bottle, cloths hanging clipper etc. as shown in figure 10. Objects were chosen to have different variety of shapes as compared to previous literature [48].

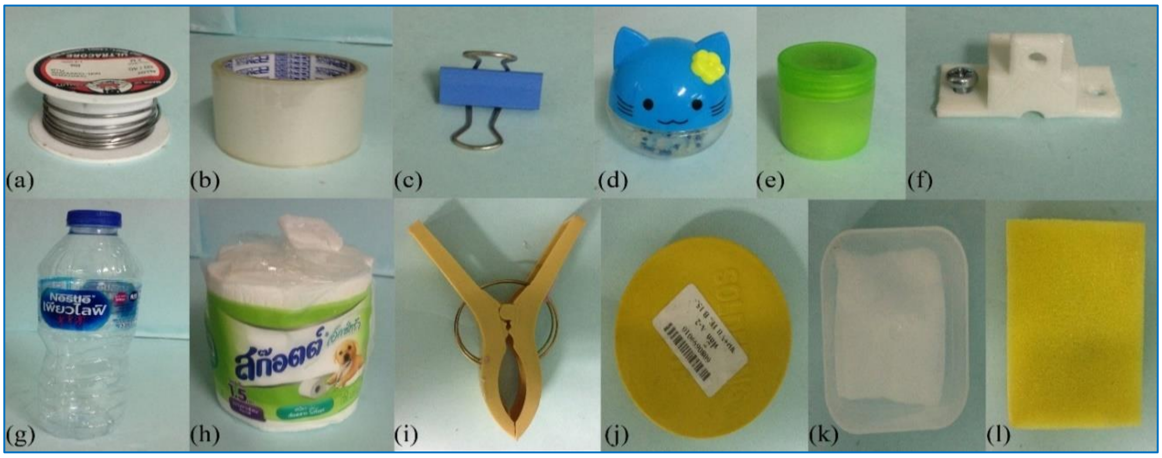


Figure 10. different objects to test gripper performance: (a) Soldering coil, (b) Scotch tape, (c) Paper holder, (d) Wind-up toy, (e) Small bottle, (f) 3D printed part, (g) Water bottle, (h) Tissue paper role, (i) Cloth hanging holder, (j) Circular plate, (k) Square box, (l) Sponge foam.

As being inspired from human hand anatomy, three actuators were chosen for testing the grasping ability. Each gasping entity has the same distance from each other to have reliable grasping. Figure 11 explain the movement of gripper. Moreover, each entity was mounted on the base such that it can bend inner-ward in order to grasp the object, and upon release, can automatically release the object in grasp.

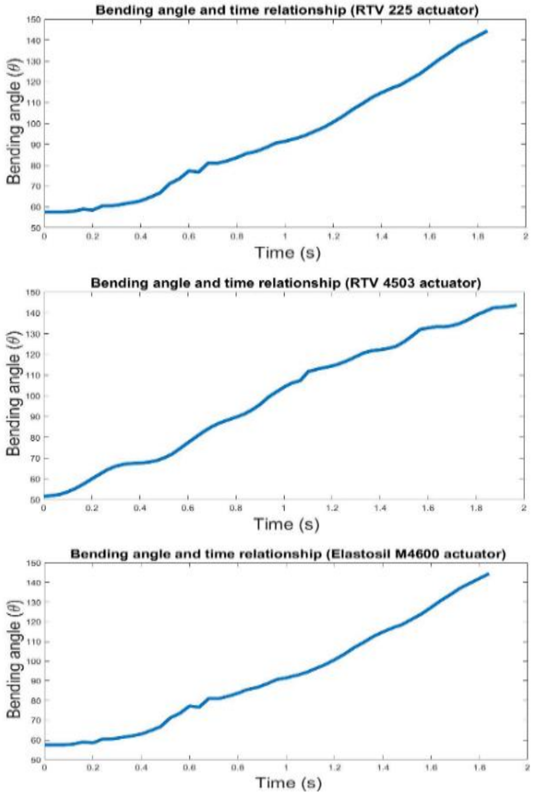


Figure 9. time and bending angle relationship for RTV 4503, RTV 225 and Elastosil M4600.

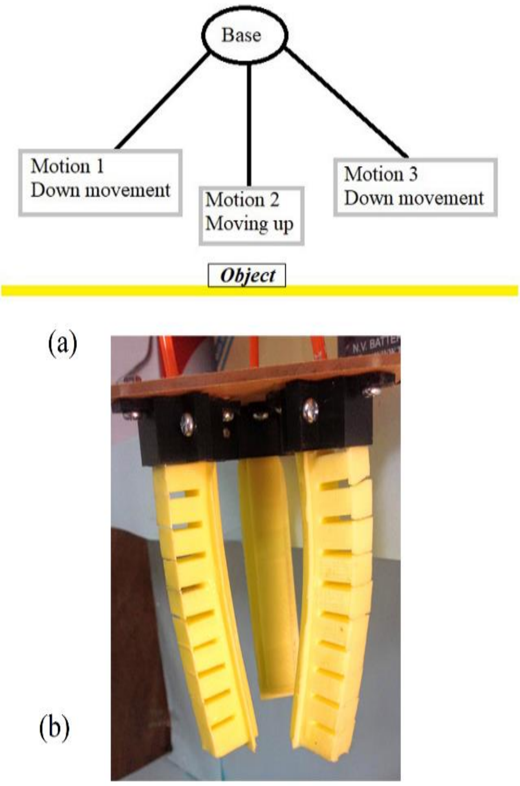


Figure 11. **gripper movement:** (a) motion 1 explain the gripper moving down and grasping, motion 2 describe the movement of gripper with grasped object, motion 3 describe the gripper movement down and releasing the object, (b) Gripper assembly and orientation.

Table 3. shows the values of objects weight and pressure applied to grasp those objects.

Table 3. Objects weight, grasping pressure for each gripper and shape of objects

Object	Weight (g)	Pressure (KPa) RTV 225	Pressure (KPa) RTV 4503	Pressure (KPa) Elastosil M4600	Shape
Soldering Coil	9.75	23	22	25	Hollow circular
Scotch tape	80.99	20	21	27	circular
Paper holder	6.94	28	25	30	Irregular
Wind-up toy	29.66	19	21	24	Irregular circular
Small bottle	8.97	29	27	-	circular
3D printed part	4.07	24	25	-	Square body
Water bottle	13.31	18	20	22	Circular
Tissue paper role	67.80	13	15	19	Circular

Cloth hanger	21.30	27	23	30	Irregular
Circular plate	7.32	16	17	19	Circular
Square box	11.95	21	19	25	Square body
Sponge foam	5.24	18	16	14	Regular square

Figure 12 shows the experimental result of grasping the target objects shown in figure 10. Gripper assembled with RTV 225 and RTV 4503 shows the reliable gripping of objects. Gripper assembled with M4600 shows reliable grasping with object having large diameter but didn’t grasp some objects. Object having higher weight require more pressure as compared to low weight objects.

Figure 12. Grasping experiment with different objects using all three material actuator type.

5. **Discussion**:

As shown in figure (12a) and (12b), soft gripper shows the reliable grasp over all the target objects. Figure (12a) shows the grasping results of RTV 4503. Result shows that gripper reliably grasp the object ranging from 80.99-4.07 g with a range of grasping pressure of 27-15 kPa. While gripper assembled with RTV 225 (Figure 12-b) actuators also shows the same reliability of grasping with same range as mentioned above with pressure range of 27-16 kPa. Gripper assembled with Elastosil M4600 shows the reliable grasping of object having large diameter but relatively less reliable with small diameter objects as shown in figure (12c). Elastosil M4600 gripper required more pressure for grasping as it's hardness is larger as compared to RTV series silicones.

Some of the Elastosil M4600 actuator shows higher inflation (more than desired) at some chambers which effects the reliability of gripping while handling small objects. On the other hand, RTV series shows the reliable gripping due to their linear bending with inlet pressure. RTV series grippers show small slip over grasping object due to low material friction and minimum surface area of actuator that directly holds the object. This can be handled by quantity of oil to reduce the concentration level of RTV silicones and increasing its density which may enhance its grip over objects as well as by expanding the minimum contacts from 3 to 4 or more.

The uniaxial tensile test identified some properties of these three materials. Elastosil M4600 have highest elongation and tensile strength but experiment shows high inflation at some chambers. Elastosil M4600 shows the large number of bubbles as compared to RTV series silicones while mixing which also can be reason of higher inflation in some chambers of actuators. M4600 takes higher vacuum pressure for degassing as compared to RTV series silicones.

It has been observed in that higher stiffness required higher pressure for full bending which can be seen in experiments. It's also observed that higher stiffness material gripper shows more gripping contact with the target object. Higher stiffness material gripper takes longer time to achieve full bending as compared to small stiffness material. From these observations, we can increase the stiffness of RTV series by adjusting the curing agent with delicate fabrication process. In terms of overall performance and tensile test results, we can say that actuator fabricated with RTV 225 and assembled gripper with it shows more promising future.

6. Conclusion:

In this paper, we presented design, fabrication/assembling and experimental evaluation of a three-contact-point pneumatic gripper made with three different soft materials. Material properties for materials were examined with uniaxial tensile test. The performance of pneumatic actuator can be described by speed of actuation, actuation pressure and bending (inflation) degree. Experiments were conducted to characterize the bending angle, actuation pressure, pressure at full bending and actuation speed. These actuators can achieve full bending at very low pressure below 55 kPa with very less time of 1.8s – 2.5s. The proposed materials reduced the cost of fabrication and shows a possible soft material for soft robotic projects. For grasping/manipulation the delicate objects ranging from daily living activities to industry object. Grippers showed the reliable gripping for delicate objects. The fabricated actuator and assembled gripper were tested with open loop strategy where actuator shows the full bending and grippers shows the reliable grasping of different objects with potential to meet practical applications.

Further investigation about the effect of curing agent on shore hardness can be done. The actuation control system can be developed on close loop strategy to improve the portability and performance of actuators and grippers.

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Appendix C

Amir Souhail and Passakorn Vessakosol, “Low Cost Soft Robotic Gloves for at-Home Rehabilitation and Daily Living Activities” submitted to be published in Topics in Stroke Rehabilitation (ISSN: 1074-9357, 1945-5119)

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 shows 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 which 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, 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. This 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 that hypothesis that rehabilitation with robotic devices is a promising approach in hand therapy[17].

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

Robotic devices for rehabilitation is a fast growing field in recent years. There is 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.

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

Table. 1. Previously developed hardware systems and their specification

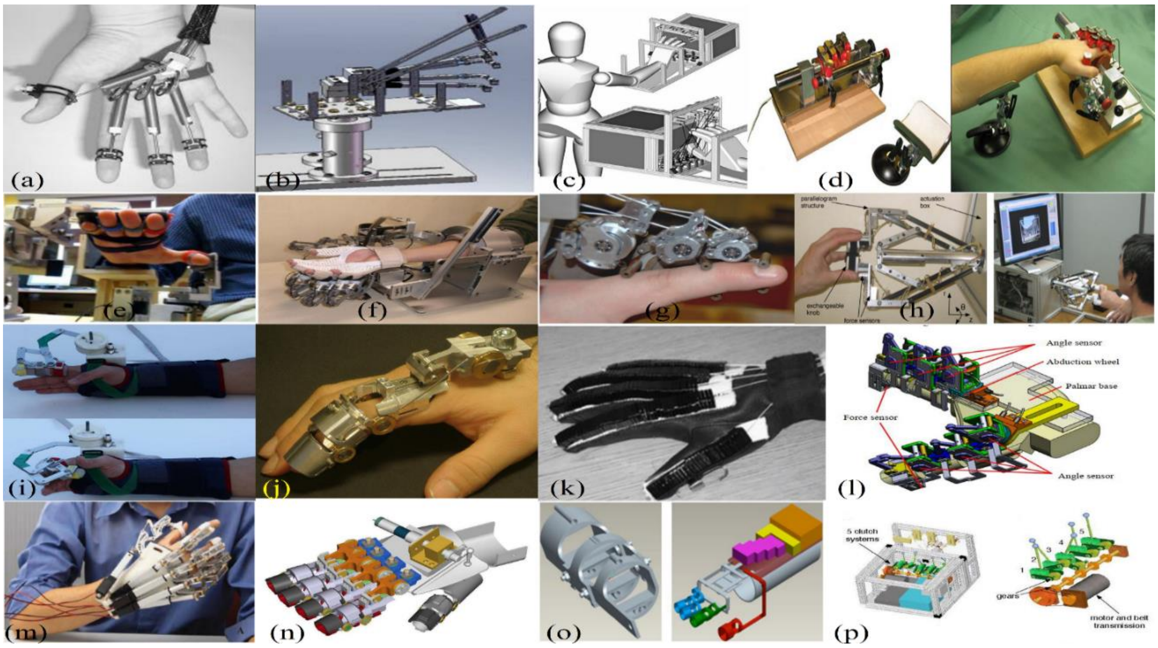


Figure. 1 Rigid body rehabilitation robots: (a) The Rutgers Master II [23], (b) Interactive rehabilitation robot [24] ,(c) HandCARE [25], (d) Electromechanical trainer [26] ,(e) HEXORR [27] (f) Finger exoskeleton [24] ,(g) Thumb exoskeleton [30] , (h) Haptic Knob [34] (i) EMG-driven exoskeleton hand 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]

Rigidness, complexity and heaviness of these system is an obstacle in using them out of rehabilitation centres and without help of therapist. Lack of compliance (stiffness and softness) is always a problem in rehabilitation devices[43].Bulkiness of these device make it uncomfortable for using it for stroke effected hand. Components of these devices like motor and material put more stress on effected parts of the hand. While considering these limitation , 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.

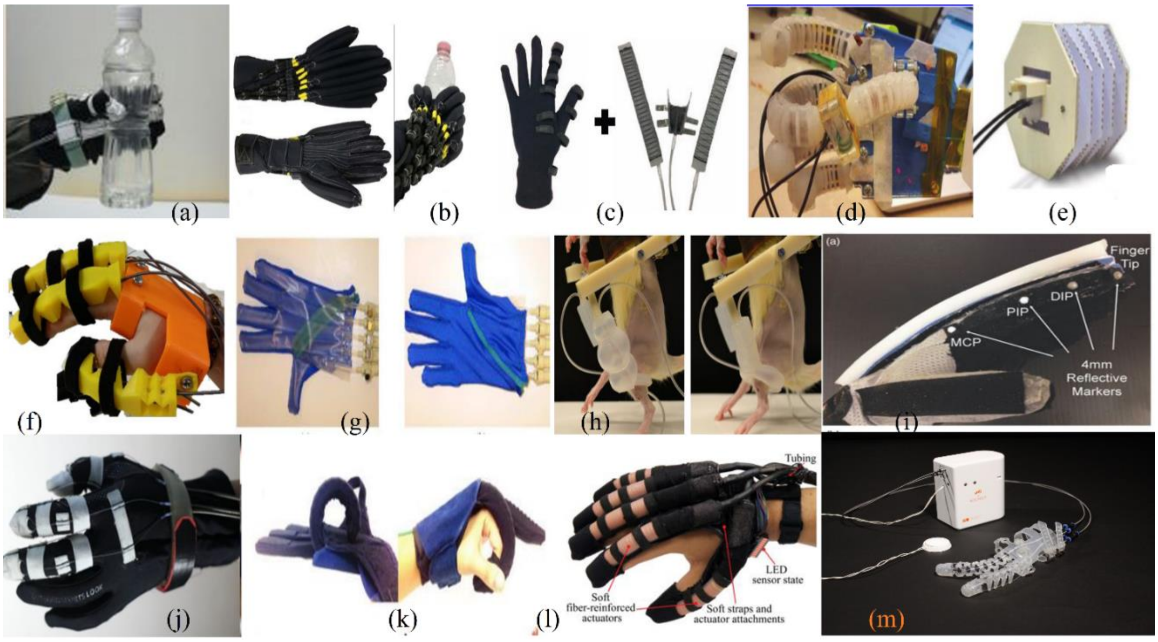


Figure 2. soft robotic gloves found in literature: (a)Exo-Glove wearable glove base on tendon routing system [45], (b) AirExglove A pneumatic and tendon routing system wearable glove [58], (c) A pneumatic wearable soft robotic glove [59], (d) Shape memory alloys (SMA's) glove [60] (e) Pneumatic actuator 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].

A wearable soft robotic glove can lead rehabilitation process at home by providing 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.

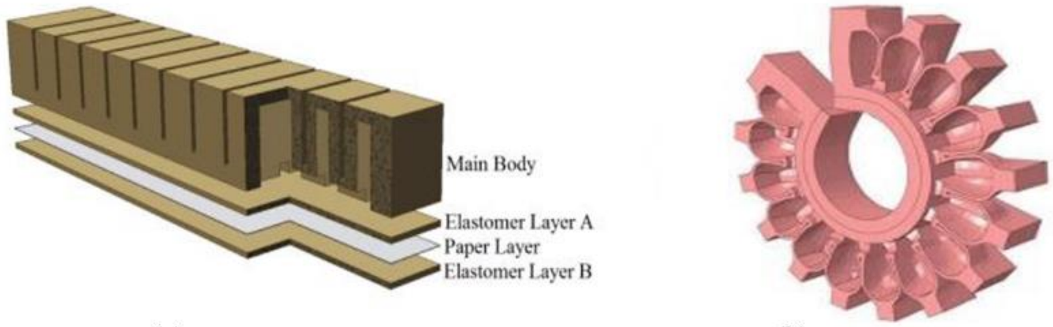
This paper presents a soft robotic glove for rehabilitation which use the inexpensive silicon for fabricating the actuator which are actuated by air pressure. Air pressure helps the biological designed fingers for flexing and extending the hand as glove will be attached on the dorsal side of hand which help 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 glove presented in this work operate with pneumatic (air) pressure which provides the grasping and releasing (extension and flexion) the human hand for rehabilitation practice and daily living activities. Glove is 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.

2.1. Single pneumatic actuator

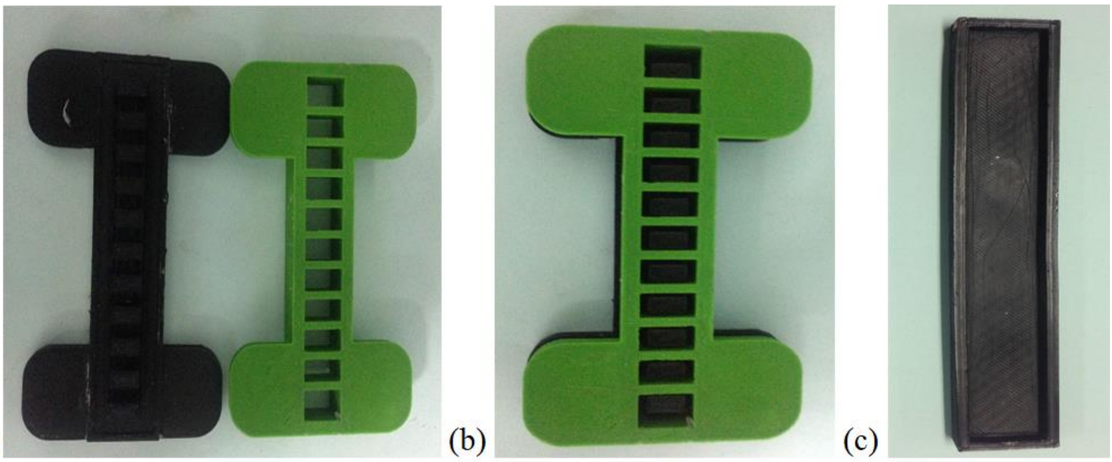
Soft Pneumatic actuator is based on the design presented by [64] which shows fast actuation. Pneumatic actuator consists of three layers which include extensible top layer which have air chambers, inextensible layer and extensible base layer to enclose both layers as shown in figure (3-a).



(a) (b)

Figure 3. Soft pneumatic actuator design configuration: (a) different layers of the actuators are labelled, [65] (b) expected bending behavior of the actuator [64].

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.



(a) (b) (c)

Figure 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 1.

Properties	Silicon (RTV 225)	Silicon (RTV4503)	Elastosil M4600
Tensile strength (N/mm^2)	≥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/mm^2)	≥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/cm^3)	-	Approximately 1.16	1.1

Density at 23° in water (g/cm^3)	-	1.16	1.1
Elongation at break (%)	≥420	400	800

Table 2. Properties of silicon used in fabrication process

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 2 and table 3 shows the mixing ratios of RTV 225 and RTV 4503 part A, part B (curing agent) and paraffin oil. A range of mixing ratios for part A and part B found during the experiment which varies from 2.00-2.50 (g) for RTV 4503 while 1.00-1.50 (g) for RTV 225.

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

Table 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

Table 4. Mixing ratios of RTV 225 Silicone elastomer

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 cause 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.

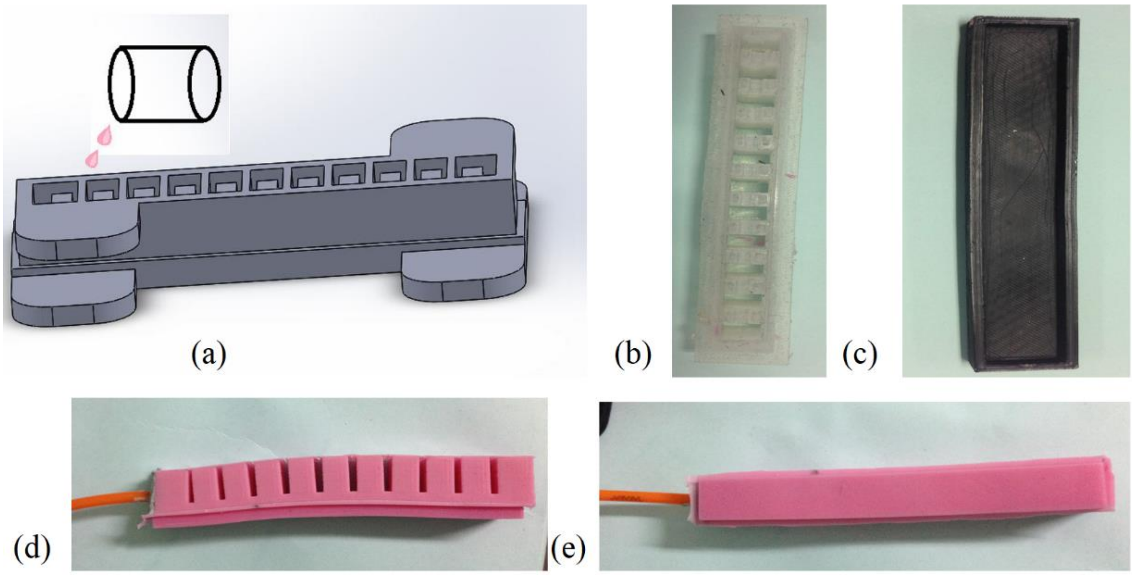


Figure 5. Fabrication process of single actuator: (a) stirred mixture was poured directly into mold and left for curing (b) fabricated air chamber (top layer) after

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.

4. Results

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

4.1. Blocked test force measurement

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 1.36 N, 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 [66]. RTV 4503 and RTV 225 stiffness can be increased or decreased by 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.

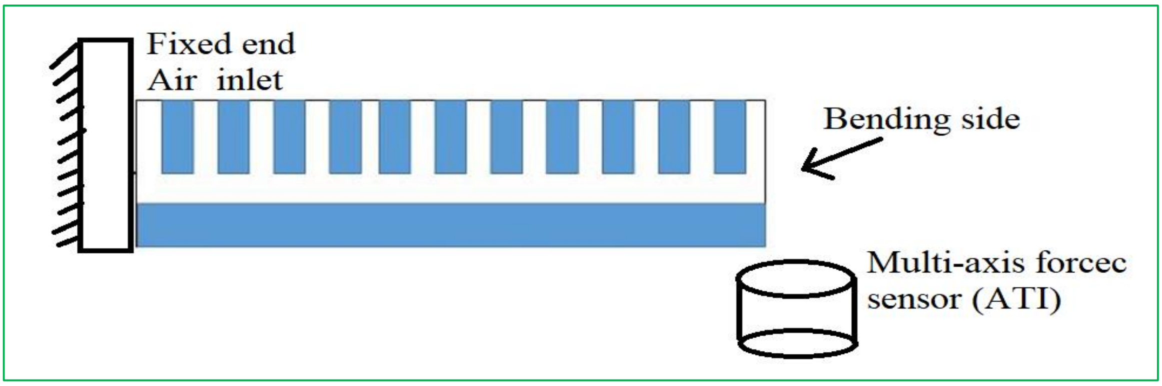


Figure 6. Experimental setup for blocked force test.

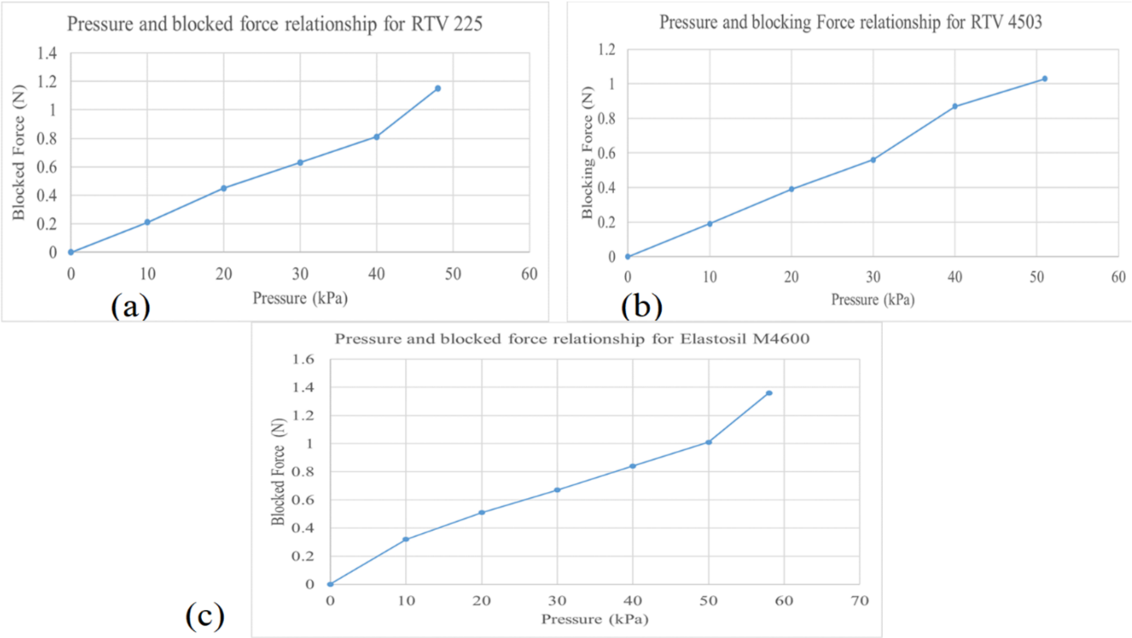


Figure 7. Pressure and blocked force test for RTV 225, RTV 4503 and Elastosil M4600 fabricated actuators

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 trajectory of 49° at initial position for Elastosil M4600 fabricated actuator while RTV series silicones shows higher free travel trajectory of 59° and 53° for RTV 225 and RTV 4503 respectively. Higher free travel trajectory was observed and it can be explained by the lower stiffness of materials.

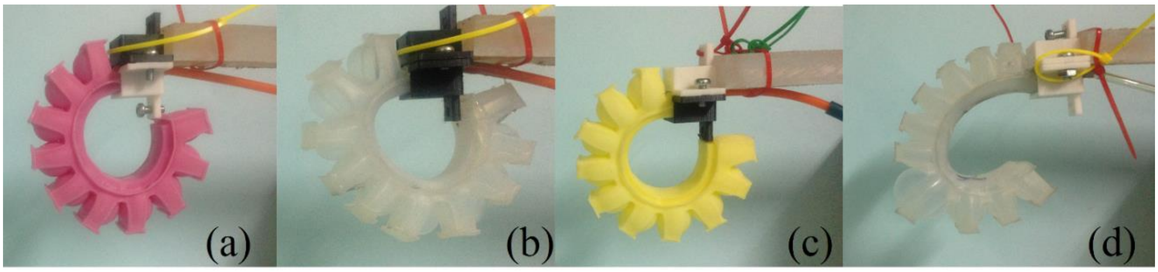


Figure 8. setup for free travel trajectory tracking test: (a) Full bending for RTV 225 fabricated actuator, (b) Full bending for Elastosil M4600 fabricated actuator, (c) Full bending for RTV 4503 fabricated actuator, (d) Some of the Elastosil M4600 actuator shows extra inflation at some chamber.

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.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 finger 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).

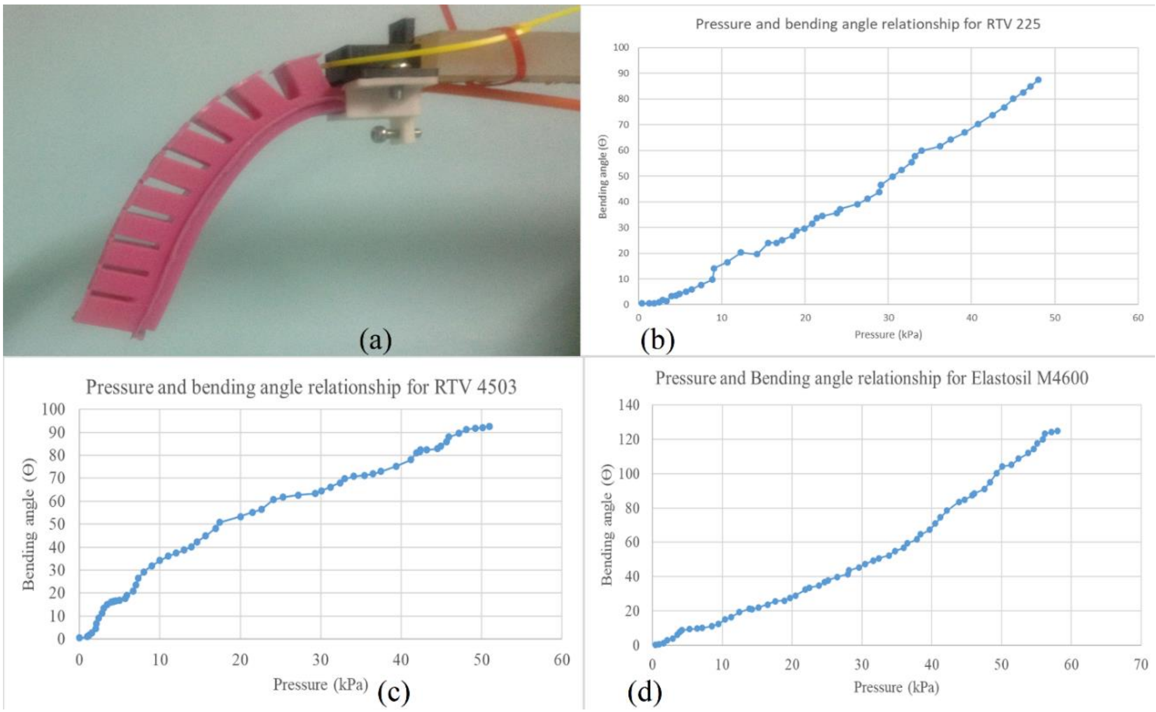


Figure 9. setup for estimating bending angle variation with pressure: (a) Experimental setup and bending angle definition, (b) Pressure and bending angle for

RTV 225, (c) Pressure and bending angle for RTV 4503, (d) Pressure and bending angle for Elastosil M4600.

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. Figure 10 (a) shows the thumb interaction with index finger while figure (10-b) shows the index finger flexion. Figure (10-c) and (10-d) shows the flexion of human hand when pressurized.

Different objects were chosen to test the grasping ability which include a) small bottle b) small water bottle c) coffee cup and d) telephone receiver. The grasping pressure was measured as 23 kPa, 26 kPa, 31 kPa and 45 kPa in robotic glove assembled with RTV 4503 actuators while 21 kPa, 24 kPa, 35 kPa and 48 kPa in RTV 225 assembled robotic glove respectively for each object as shown in figure 10.

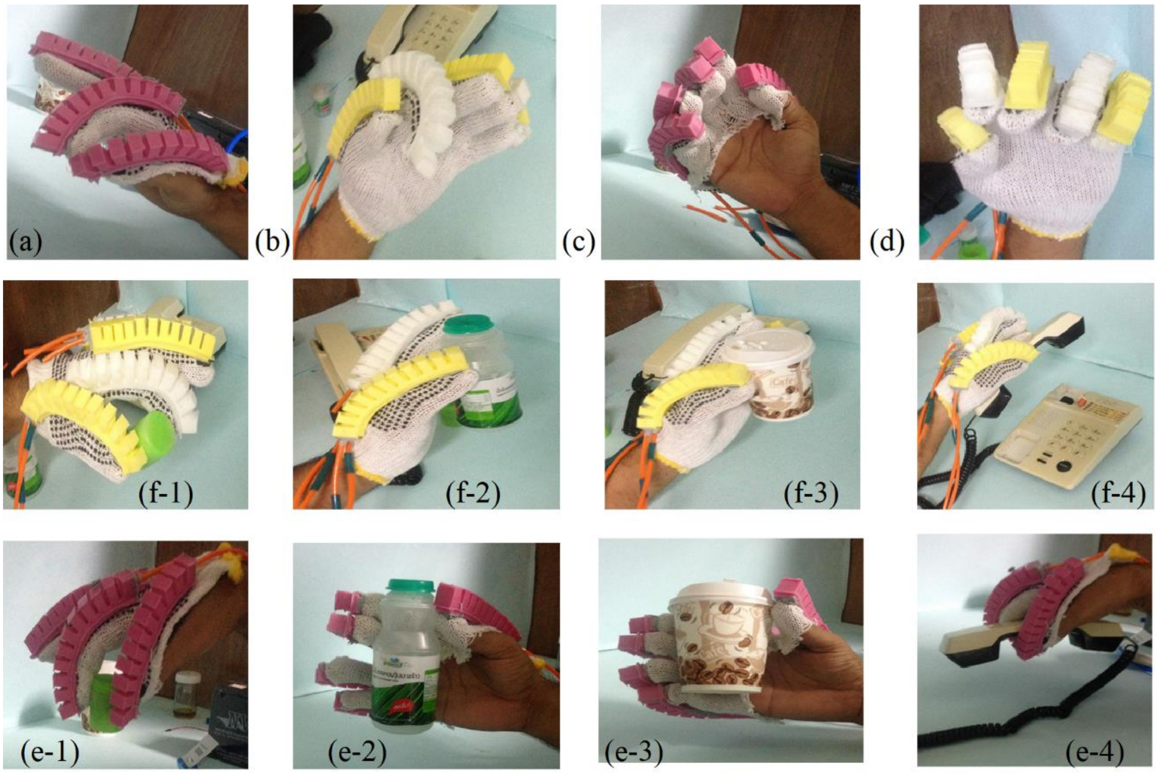


Figure 10. Grasping ability test for soft robotic glove: (a) Pinching pose with thumb and index finger (RTV 225) (b) Index finger bending (RTV 4503) (c) Full hand flexion with robotic glove (RTV 225) (d) Full hand flexion with robotic glove (RTV 4503) (f-1, e-1) Grasping a small bottle with pinching 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.

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 [68] is one of these test which implemented on healthy subject. Figure 10 shows the hand postures for standardize Kapandji test and hand flexion.

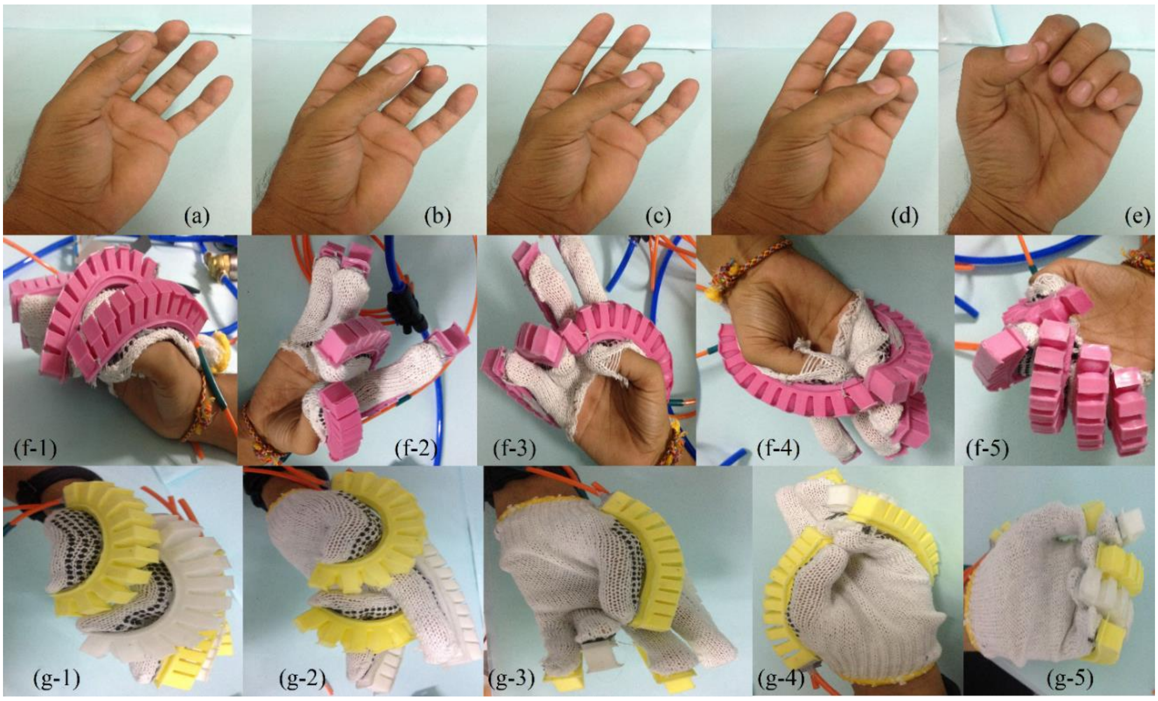


Figure 11. Kapandji test for rehabilitation purpose: (a) thumb contact with index finger (b) thumb contact with middle finger (c) thumb contact with ring finger (d) thumb contact with small finger (e) full hand flexion (f-1 – f-4) soft robotic glove assembled with RTV 225 performing all above posture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

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 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 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 with [69][70][71]. 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. 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, endurability, and lower curing time.
- It has been observed that direct stirring causes a large number of air bubbles inside the mix solution for which higher vacuum inside the chamber need. Trying different mixing method can reduce the air bubble production inside solution.
- Block force magnitude can be increase by increasing the hardness of materials which result in bearing more pressure to generate more 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. 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 for 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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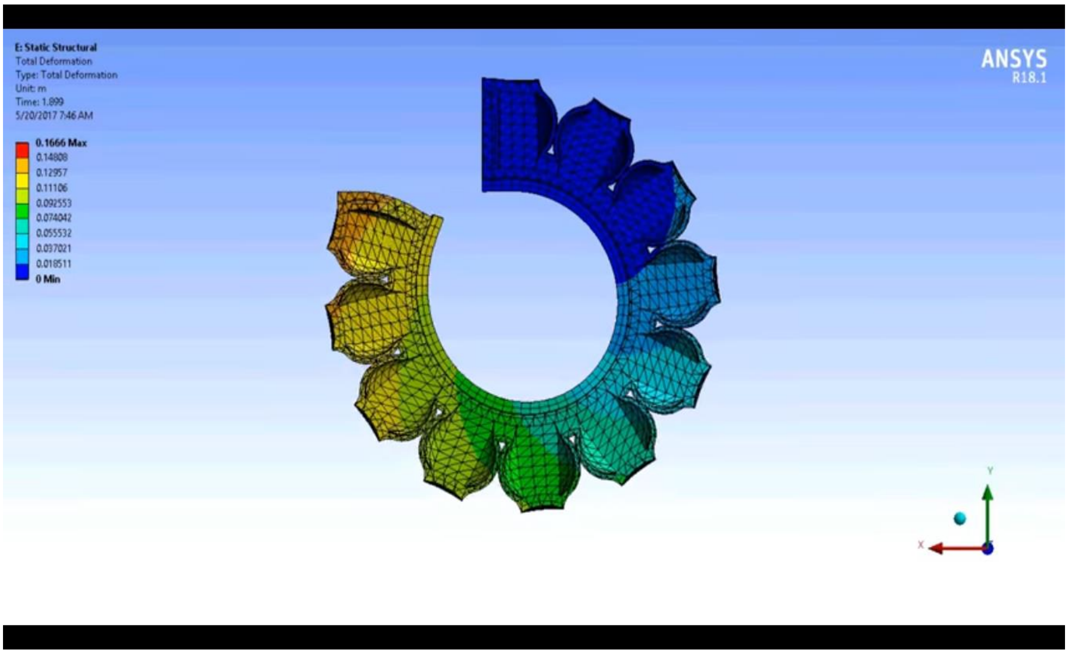
Appendix D

FEM modeling result for Pneumatic actuator with Elastosil M4601



Ogden coefficients for RTV 225 using two different software's

Material Parameters Ogden model with Hyperfit		Material Parameters Ogden model with MCalibration	
Name	Value	Name	Value
µ 1	2.85795243	µ 1	0.281791
ά 1	1.532600839	ά 1	2.20826
µ 2	-9.76140479	µ 2	0.515872
ά 2	0.597603432	ά 2	2.0765
µ 3	7.071411651	µ 3	-0.747326
ά 3	0.15140489	ά 3	1.22432
D 1	0	D 1	0.02
D 2	0	D 2	0.02
D3	0	D3	0.02

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List of Publication and Proceeding

1. Amir Souhail and Passakorn Vessakosol, “PneuNets Bending Actuator Design and Fabrication Using Low Cost Silicones,” in The 9th TSME International Conference on Mechanical Engineering, 2018 (**Manuscript Accepted**).
2. Amir Souhail, Passakorn Vessakosol (2018). Low Cost Soft Robotic Grippers For Reliable Grasping. Journal of Mechanical Engineering Research & Developments, 41(4):88-95
3. Amir Souhail and Passakorn Vessakosol, “Low Cost Soft Robotic Gloves for at-Home Rehabilitation and Daily Living Activities” submitted to be published in Topics in Stroke Rehabilitation (ISSN: 1074-9357, 1945-5119)