

Design of a Soft Robotic Glove for Hand Rehabilitation Based on Pneumatic Network Method and Low Cost Electro-pneumatic Device



Boi Mai Quach, Vo Van Toi, and Hien Thi Thu Pham

Abstract The state-of-the-art field of bio-inspired soft robotics promises emergent and inventive methods to utilize robots made from soft, flexible materials in a wide range of applications. This research is on-trend, describes an advancement in the design of a wearable robotic glove to assist people suffering from hand impairments regain their ability to control their environment. This study built a streamlined, inexpensive electro-pneumatic system that can work with small and simple actuators to increase for finger movement flexibility. The use of pneumatic pressure to stretch and bend the actuators through inflation or deformation of elastic chambers, making this glove work effectively. The designed pneumatic device consists of STM32F101C8T6 microcontroller combined with a series of pumps and a matrix of solenoid valves. Along with the electro-pneumatic system, we also applied it to develop a wearable robotic glove (made from Ecoflex™ rubbers) which is suitable for the pneumatic system by the series of experiments that mechanically characterize the actuators. The results gathered in this study validate the feasibility of the first prototype of our soft robotic glove as an effective device to assist hand function in individuals. However, performance and ease of use of the system should be improved further in future development phases.

Keywords Soft robotics · Electro-pneumatic · Fluidic · Hydraulic

1 Introduction

The majority of hand disability patients undergo a stroke, Duchene/Becker muscular dystrophy or incomplete spinal cord injury [1, 2], experience an absence of hand motor ability, extremely restrict activities on a daily basis and markedly reducing living standards [3]. Physical therapies are currently involved in practicing required tasks repetitively for patients to improve hand strength, precisely, and movement

B. M. Quach (✉) · V. Van Toi · H. T. T. Pham
School of Biomedical Engineering, International University, Ho Chi Minh City, Vietnam
Vietnam National University, Ho Chi Minh City, Vietnam

ability [3, 4]. However, these therapies need more support from technicians and more time to observe and analyze the patient's performances, which raises a high demand for the physical therapists [5]. From the limitations of traditional robotic instruments, medical specialists hope to find out alternative methods, and soft robotics seems to be an effective adoption. Soft robotics is made of materials which are similar in characteristics to human tissues. This method is an emerging field that has drawn increasing interest since their ability to interact with highly advanced eco-friendly environments without destructive impacts or self-damage compared with their heavy and redundant equivalents.

In this research, to operate the soft robotic hand glove, an inexpensive and portable electro-pneumatic control system was designed and included pneumatic (air) pressure sensors in line with a closed-loop controller to regulate the pressure. The problem to be solved here was reducing cost but keep relative its functions. Thus, all components had to be found easily with an economical cost. Another step to this project was to create a soft robotic glove which could lead to greater advances in physical therapy at home by providing: (a) more flexible in controlling hand movement, (b) an easily used robot for normal people, (c) safe interaction since the softness and compliance with their fabrication, (d) portability. It was also a perfect demo for the electro-pneumatic 's applications since it is reality and medical meaning.

The rest of paper is organized as follows: First, we briefly review the works on soft robotic glove and systems are used to control the robotic devices. The next section gives the methodology about designing a pneumatic network and making a soft robotic glove. We then exhibit the results of the whole procedure (hardware, calibration, software). Finally, we conclude the discussion and discuss the research plans for our future work.

2 Related Work

Soft robots can better adapt to their surroundings [6], perform differently and even multi-task, and can imitate the motion and function of biological systems, such as octopus's tentacles [7, 8] or movement of worms [9]. In biomedical engineering, and medical in general, there has been rising interest in numerous possible applications of soft robotics systems into various orientations and clinical settings. Actuator material and actuation method make it lightweight and easy to use for education and training of medical professionals, robotic organs, mechanotherapy, autonomous minimally invasive surgery, etc. In the literature, the soft robotic gloves for hand physical therapies, especially in stroke, are referred to as Table 1.

In these references, there are many different designs and actuation methods such as Shape memory alloys (SMA) driven actuators, Tendon driven actuators, Fluid driven actuator and Pneumatic actuators have been developed for robotic rehabilitation 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 to 500 °C [12]. The complex design of SMA actuators

Table 1 Soft robotic gloves found in the literature

Reference, Developer	System	Type of usage	Supported movement
Exo-Glove [10]	Tendon routing system	Grasping of objects	Wrist, elbow, shoulder joints, full hand
AirExGlove [11]	Pneumatic actuators and Tendon routing system	Rehabilitation	Full hand
SMA's glove [12]	SMA (Shape memory alloys) actuators	Rehabilitation	Full hand
PneuGlove [13]	Pneumatic actuators	Rehabilitation	Full hand
Pneumatically actuated robotic glove controlled with EMG [14]	Pneumatic actuators and Surface Electromyography (sEMG)	Rehabilitation	Full hand
GRIPIT [15]	Tendon routing mechanism and Tension maintenance mechanism	Tripod grasp	Thumb, index finger, and middle finger
Soft Anthropomorphic Robotic Hand [16]	Kirigami-inspired system and Origami structure	Rehabilitation	One finger at one time
Gait rehabilitation soft robot [17]	Soft pneumatic actuators (SPAs)	Gait rehabilitation	Specialized animal
Fluidic actuated soft robotic glove [18]	Hydraulically actuated multi-segment soft actuators	Rehabilitation	Full hand
Wearable haptic device [19]	Haptic systems	Rehabilitation	One finger at one time

made it difficult to use in rehabilitation purposes and daily living activities. The fluid-driven actuator is no nifty portable and high user maintenance throughout the life of the system. Pneumatic actuators were selected due to higher stiffness, low weight and simpler design than the actuators mentioned above.

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. The glove will be attached on the hand's dorsal side which helps the patient feel the objects more naturally. Actuation energy source and electro-mechanical components are mounted separately to put them as low as the human finger's burden.

3 Methods

3.1 Design Elastomeric Materials

In this work, we proposed an easy and quick fabrication method of soft inflatable plastic actuators. Ecoflex™ rubbers, which are platinum-catalyzed silicones produced by Smooth-On, Inc, are commonly used in the making of prosthetic appliances, cushioning for orthotics and special effects applications. Its notable characteristics include the un-cured silicone (easy to mix, disperse and degas). The cured material is soft, flexible and remarkably strong, being able to stretch several times exceed the original size and then rebound back without deforming. Other beneficial traits include colorlessness, quick cure time, minimal shrinkage, and safety.

In order to cast silicon rubber, casting 3D molds are designed and include two main parts: an upper part with hollow chambers (air bladder) and a base made of pliable but non-elastic material such as fabrics or paper, or with the same material as the upper part but are completely dense. After the materials have been prepared, the single actuator's fabrication process is mainly developed in the laboratory and is described briefly in Fig. 1.

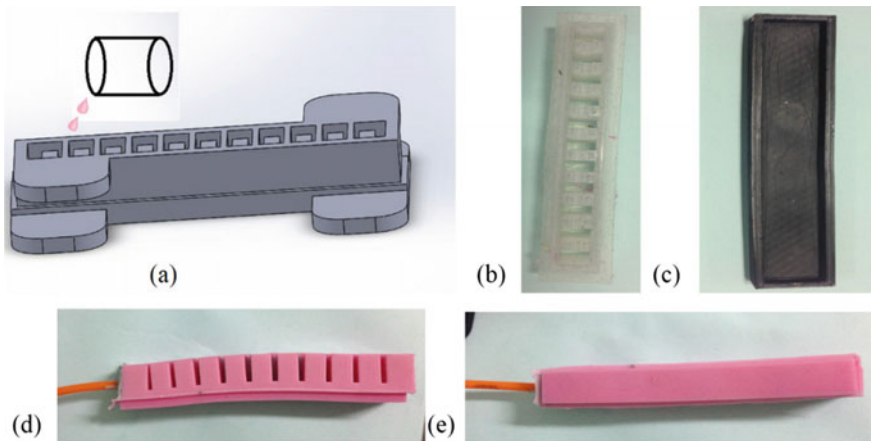


Fig. 1 Fabrication process. **a, c** Stirred liquid rubber was poured directly into the upper and bottom part and left to solidify. Then a paper or fabric layer was inserted and poured some more silicon which glued the base part. **b** Fabricated air chamber (top layer) after demolding. **d** Side view of fabricated actuator after inserting the pipe for air supply. **e** Bottom view of the actuator

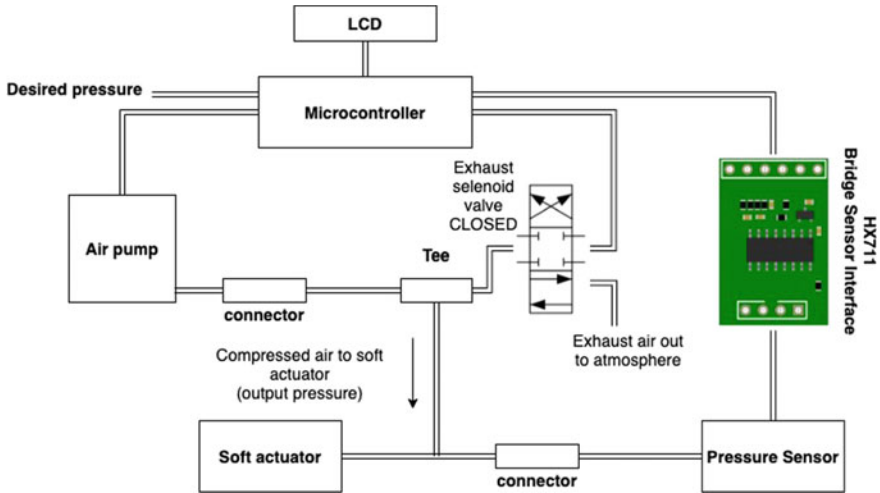


Fig. 2 Block diagram of the electro-pneumatic board

3.2 Electro-pneumatic Design

In order to control the hand prosthesis, it was assembled an electro-pneumatic circuit, presented in Fig. 2, consisting of a series of pumps which navigate the external airflow to the system and a matrix of solenoid valves which are used to open and close to regulate the flow of fluid in the system. The system’s pressure is controlled based on PWM (Pulse-Width Modulation) principle, which involves the controlled timing of the activation and deactivation of the electrically controlled valves. Pressure sensor (XGZP101) provides feedback on system’s behaviour after the analog signals are converted by HX711 (amplifier interface). May manually, change the state of knobs to control the device because each knob represents potential changes in the STM32F101C8T6 microcontroller. Additionally, the microcontroller will analyze the data collected from the sensor and convert them into digital signals before displaying on LCD.

Based on the control parts such as the matrix of buttons, pumps, and the valves system, the logic system will be designed in term of SPDT switches to control the actuators’ inflation and deflation phases. These digital pins were connected to inputs. The chambers were able to inflate or deflate depending on the state of the outputs.

3.3 Pressure Sensor Calibration

The XGZP101 pressure sensor is an analogue pressure sensor. If the differential pressure is applied on the sensor, the sensor will deliver an analog output voltage proportional to the corresponding pressure. It is a gauge pressure sensor meaning

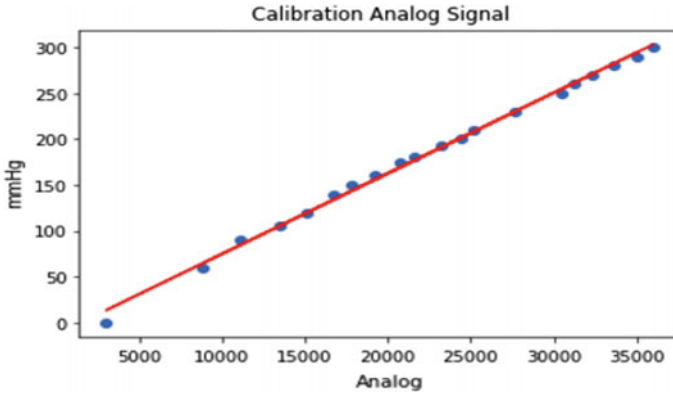


Fig. 3 Pressure and relative analog signal data and the best-fit line

that it measures the pressure in excess of atmospheric pressure from -15 to 15 psi. Using HX711 to convert analog signal up to 24 bit. After the collection of data, we indicated them on the graph and find the best-fit line as well as calculated the final Eq. (1):

$$y = -30.39 + 0.01 * x \quad (1)$$

where y is the pressure value (unit: mmHg), x is the analog signal. The collected data used for calibration and the best-fit line are shown in Fig. 3.

4 Experimental Test and Results

4.1 Electro-pneumatic System

Using SolidWorks drawings, the hardware was constructed by either mechanical work or 3D printing. An electro-pneumatic system (total weight is approximately 1.70 kg) allowed to navigate individual actuators, was assembled as Fig. 4.

The system has a two-dimensional array with white buttons, includes in two parts. Ten buttons on the left side will regulate solenoid valves and pumps connected with each finger, respectively. When we press the buttons on the top, the pumps active and the valves will be closed to release the air flows into the actuators. By contrast, the pumps will be stopped, and the solenoid valves are opened to release the airflow out of the environment if we press the buttons on the bottom. We designed two buttons on the right side and the same side with the power switch to change the state exercises. The one below will be active to control all fingers at the same time, and the other one will be the state which each finger can be activated independently. The blue rotate button in the top left corner of the box is a variable resistor to speed



Fig. 4 The portable control box

up the airflow movement from the pumps releasing. The LCD always displays all instructions to guide users, and the air pressure and the force value are also shown during the process.

Figure 5 illustrates the result of pressure after calibration. The green line describes the measured air pressure (P) and the pink line as the regression model's output. The trend of both two values follows a pattern.

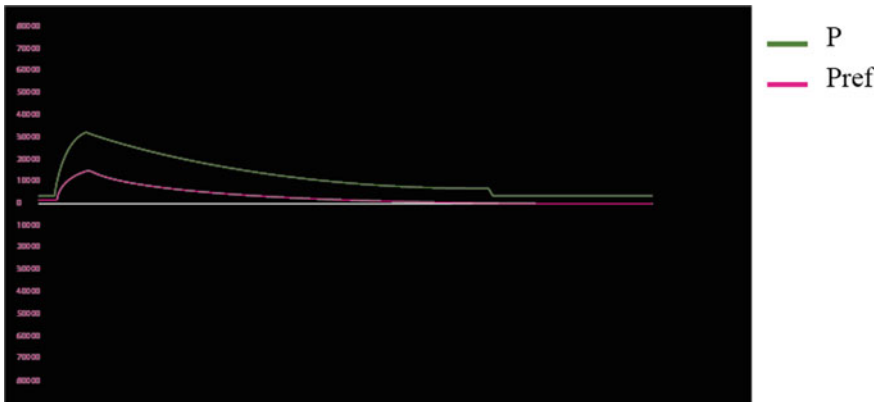


Fig. 5 The result of calibration

4.2 Force Measurement

The blocking force was designed to measure the force generated by soft actuators as Fig. 6. One end of the actuator was fixed to act as a cantilever beam, and the other was free to measure the force. When the air is inhaled, the figure bent and touched the *FSG15N1A* sensor and then the analog data will be collected.

The experimental result of blocked force and input pressure relationship for the finger is shown in Fig. 7. The maximum pressure from the air which the finger, made from *Ecoflex™* rubbers, can withstand is approximately 120 kPa.

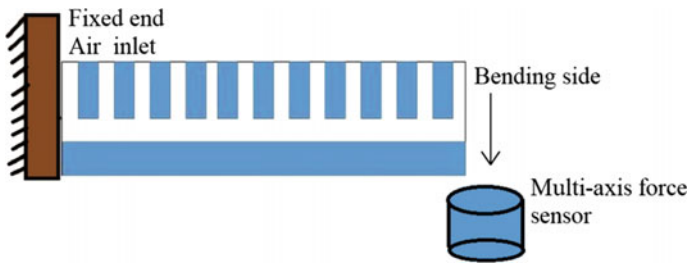


Fig. 6 Experimental setup for blocked force test

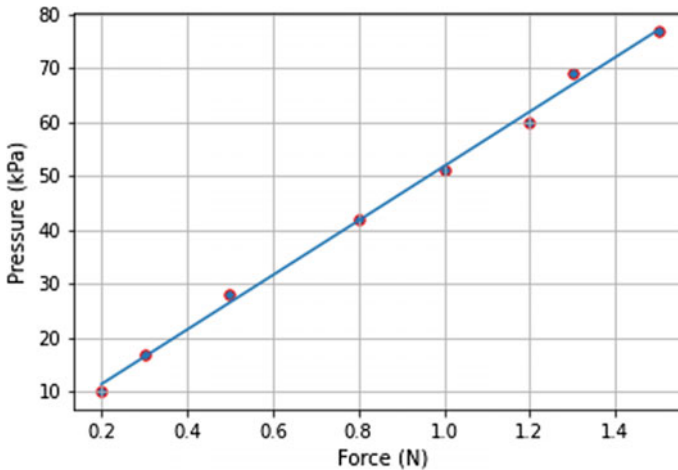


Fig. 7 Pressure and blocked force relationship

4.3 Grasping of Objects of Various Shapes

In the experiments, the participants are both a healthy subject and the disabled subject. In order for users to implement a series of grasp-transport-release practices, we selected four objects which are different size and weight: (1) a plastic bottle of water, (2) a baseball, (3) a mouse, and (4) a smartphone. During the experiment, individuals must navigate each finger's direction and synchronize fingers with whole hand operation. The soft robotic glove is more streamlined than the cumbersome robot hand, which is used in the hospital currently. Figure 8 shows the grasp performance of the disabled subject while using the glove. After the experiment, most participants were very satisfied with the aid hand glove since they could grasp various objects by themselves.



(a)



(b)



(c)



(d)

Fig. 8 **a** Soft robotic glove product. **b** Grasping ability of a plastic bottle of water with full hand. **c** Grasping ability of robotic glove for a mouse. **d** Picking up a mobile phone

5 Conclusion and Future Works

In the research, we presented a soft robotic hand glove designed to aid people who undergo a decline in hand function or have congenital hand deformities through rehabilitation exercises. A low-cost device is constructed by applying the novel electro-pneumatic actuator, which made of the silicone rubber. Consequently, experimental results had achieved successful performances of a wide range of target objects. Another advantage of this mechanism is easy and cheap to manufacture because the cost of elements is reasonable (less than \$250). They are really popular in the market, or they may be recycled from used devices in the hospital. In addition, another key point is the use of hand glove allows us to exploit contacts with many difficult environments containing dirt, dust, or even liquids.

For further study, we will implement a larger study with many patients who suffer from hand muscle weakness to investigate the performance of the glove and the effects of human adaptation. More experimental exercises for many levels of grasping need to be designed for the device to be suitable with a range of patients.

Conflict of Interest The authors declare that they have no relevant financial interests in the manuscript, nor any other potential conflicts of interest.

References

1. W. G. Members, Roger VL, Go AS, Lloyd-Jones DM, Benjamin EJ, Berry JD, Borden WB, Bravata DM, Dai S, Ford ES et al (2012) Heart disease and stroke statistics—2012 update: a report from the American Heart Association. *Circulation* 125(1):e2
2. S. C. I. C. National (2014) Spinal cord injury facts and figures at a glance. *J Spinal Cord Med* 37(3):355
3. Takahashi CD, Der-Yeghiaian L, Le V, Motiwala RR, Cramer SC (2008) Robot-based hand motor therapy after stroke. *Brain* 131(2):425–437
4. Wolf SL, Winstein CJ, Miller JP, Thompson PA, Taub E, Uswatte G, Morris D, Blanton S, Nichols-Larsen D, Clark PC (2008) Retention of upper limb function in stroke survivors who have received constraint-induced movement therapy: the excite randomised trial. *Lancet Neurol* 7(1):33–40
5. Liepert J, Bauder H, Miltner WH, Taub E, Weiller C (2000) Treatment-induced cortical reorganization after stroke in humans. *Stroke* 31(6):1210–1216
6. Laschi C, Mazzolai B, Cianchetti M (2016) Soft robotics: technologies and systems pushing the boundaries of robot abilities. *Sci Robot* 1(1):eaah3690
7. Laschi C, Cianchetti M, Mazzolai B, Margheri L, Follador M, Dario P (2012) Soft robot arm inspired by the octopus. *Adv Robot* 26(7):709–727
8. Calisti M, Giorelli M, Levy G, Mazzolai B, Hochner B, Laschi C, Dario P (2011) An octopus-bioinspired solution to movement and manipulation for soft robots. *Bioinspiration Biomimetics* 6(3):036002
9. Jung K, Koo JC, Lee YK, Choi HR et al (2007) Artificial annelid robot driven by soft actuators. *Bioinspiration Biomimetics* 2(2):S42
10. In H, Kang BB, Sin M, Cho K-J (2015) Exo-glove: a wearable robot for the hand with a soft tendon routing system. *IEEE Robot Autom Mag* 22(1):97–105

11. Stilli A, Cremoni A, Bianchi M, Ridolfi A, Gerii F, Vannetti F, Wurdemann HA, Al-lotta B, Althoefer K (2018) Airexglove—a novel pneumatic exoskeleton glove for adaptive hand rehabilitation in post-stroke patients. In: 2018 IEEE international conference on soft robotics (RoboSoft). IEEE, pp 579–584
12. Shintake J, Cacucciolo V, Floreano D, Shea H (2018) Soft robotic grippers. *Adv Mater* 30(29):1707035
13. Connelly L, Jia Y, Toro ML, Stoykov ME, Kenyon RV, Kamper DG (2010) A pneumatic glove and immersive virtual reality environment for hand rehabilitative training after stroke. *IEEE Trans Neural Syst Rehabil Eng* 18(5):551–559
14. Polygerinos P, Galloway KC, Sanan S, Herman M, Walsh CJ (2015) EMG controlled soft robotic glove for assistance during activities of daily living. In: 2015 IEEE international conference on rehabilitation robotics (ICORR). IEEE, pp 55–60
15. Kim B, In H, Lee D-Y, Cho K-J (2017) Development and assessment of a hand assist device: Gripit. *J Neuroeng Rehabil* 14(1):15
16. Chan YH, Tse Z, Ren H (2017) Design evolution and pilot study for a Kirigami-inspired flexible and soft anthropomorphic robotic hand. In: 2017 18th international conference on advanced robotics (ICAR). IEEE, pp 432–437
17. Song YS, Sun YS, Van Den Brand R, Von Zitzewitz J, Micera S, Courtine G, Paik J (2013) Soft robot for gait rehabilitation of spinalized rodents. In: 2013 IEEE/RSJ international conference on intelligent robots and systems. IEEE, pp 971–976
18. Polygerinos P, Wang Z, Galloway KC, Wood RJ, Walsh CJ (2015) Soft robotic glove for combined assistance and at-home rehabilitation. *Robot Auton Syst* 73:135–143
19. Pacchierotti C, Sinclair S, Solazzi M, Frisoli A, Hayward V, Prattichizzo D (2017) Wearable haptic systems for the fingertip and the hand: taxonomy, review, and perspectives. *IEEE Trans Haptics* 10(4):580–600