Applying Soft Actuator Technology for Hand Rehabilitation

Quyen N. T. Vo, Tri T. M. Huynh, and Son V. T. Dao

Abstract In modern society, the ever-growing prevalence of stroke or hand disability, putting an extreme burden on the limited financial resources and capacities of health care providers in some of the Low and Middle-Income Countries (LMIC). Due to the large scale of flexibility and adaptability, soft robots turn into a smart solution for hand rehabilitation, especially soft pneumatic actuators. In this paper, we proposed a general design of soft robotic glove for hand rehabilitation with functional grasp pathologies by applying soft pneumatic actuator technology. Soft actuator included integrated channel connect each chamber to lead the air to go through the entire actuator and produce bending motion conforms with human finger shape and motion. Base on this aspect, before fabrication, a Finite Element Model (FEM) was built to analyze the bending curvature of these actuators. The soft actuator is cast in 3D printing molds using low-cost elastomer Ecoflex™ 0050. We carried out empirical tests to validate the findings of experimental actuators and compared them to FEM data displaying strong agreement. Finally, the design of a wearable for patients to practice rehabilitative activities such as grasping patterns. The outcome of this paper shows that the design of rehabilitation glove using soft actuator technology gave a successful solution for the health care system with low-cost material.

Keywords Soft pneumatic actuator · Soft robotic glove · Hand rehabilitation · Ecoflex™ 00-50 · FEM simulation

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1 Introduction

According to the statistics of the Association of Stroke Prevention, in Vietnam, there are approximately two thousand new cases of stroke each year. Among chronic stroke survivors, up to 92% have hemiplegia who live in the community need to be rehabilitated. For most of these cases, patients suffer loss functionality of partial or total absence of hand motor, so they require long-term care from others in living. This hampers immensely daily activities that scale down the quality of life and simultaneously incur the highest costs to the healthcare system [1]. Traditional rehabilitation supports patients in improving hand functions by requiring them to perform repetitive task practice (RTP) [1–6]. Patients might practice many exercises, including individual tasks integrated from complex motion under the help of physical therapists. However, this method is expensive due to the long training time and the use of a variety of support equipment. Therefore, there should be an accessible system that assists physical therapy and helps the patients conduct exercises on their own at home or in the clinic.

Findings of some clinical studies have demonstrated that stroke patients who perform intense, repetitive movements under robot-assisted devices could gain a significant improvement in hand rehabilitation [2]. However, conventional rehabilitation robots are usually applied rigid-body components such as iPAM robots [3], which are inflexible, heavy, and bulky. For this reason, a new type of robot adopting hyperelastic materials for the main body creates a large scale of flexibility, adaptability, and deformability for hand rehabilitation robots [4, 5].

There are various types of soft robotic hands for rehabilitation have been proposed so far. Polygerinos et al. designed an open-palm glove configuration attached to soft actuators on its top [6]. A related approach was also investigated by the Polygerinos group consisting of molded elastomeric chambers with fiber reinforcements which provided the potential to increase user a wide range of motion of individual fingers [7]. Another design methodology is composed of 3D printable soft material based on the topology optimization method showed a powerful potential in designing and fabrication [8].

In this paper, we present soft hand rehabilitation applied pneumatic networks.

(PneuNets) technique fabricating by low cost and available material, EcoflexTM 0050. The design structure is modified from Polygerinos et al. [6] by making a soft robotic glove by integrating five soft pneumatic actuators to simulate real human hands and demonstrate its feasibility for rehabilitation task with grasping test.

2 Materials and Design

2.1 *Materials*

EcoflexTM 00-50 is being used to test the material properties affecting different fabrication presenting on the bending of the SPA, encompassing grasping object test, bending angle, and actuation speed characteristics in the real situation. Finite element modelling (FEM) method is used to analyze the mechanical properties and behavior of soft actuators.

2.2 *Soft Pneumatic Actuator*

In task-specific training or training of activities of daily living (ADL), grasping exercise is found as movement on activity level, which related to the performance of patients' abilities in actual life [9].

The design for a device assisting hand rehabilitation exercises is that a glove would provide tight-fitting soft fingers that match the shape of the human fingers. The intended purpose of this design is to achieve the grasping motion of the entire hand and fingers base on the bending posture of the soft actuator when it inflates. Therefore, actuators would be mounted on a glove or wearable device that conform to the fingers in a closed fist configuration.

The conceptual function of the proposed soft glove is operated by pressure-flow (Fig. 1b). When gas is pump into a chamber made by highly deformable materials (elastomers), the pressure exerted is obtained to bend the whole actuators. Additionally, the stiffness of the elastomer and the pressure-flow rate characteristic of the pump/compressor control the reaction time of actuators. Therefore, the fingers of patients are assisted with additional force to close their fist. In this study, the glove size was determined to a medium-sized hand with all five fingers have the length of 112 mm and use the same basic actuator design.

The mathematical model was inspired by the modelling method in Hao et al. [10] and Onal et al. [11]. With two assumptions to simplify are the total length of the actuator is assumed to be constant, and there is no radial expansion in modelling.

Because most of the chambers have similar geometrical structure, the bending angle is calculated by using parameters of one chamber and then integrated. Based on the geometries, the axial stress (σ_x) in the material for the single chamber is as follows

$$\sigma_x = P_A = \frac{\mathrm{Pwh}}{(2\mathrm{h} + \mathrm{w} + 2\mathrm{t})\mathrm{t}} \tag{1}$$

where P is the pressure exerted on the inside walls of the chamber; w, h, and t are described in Fig. 2.

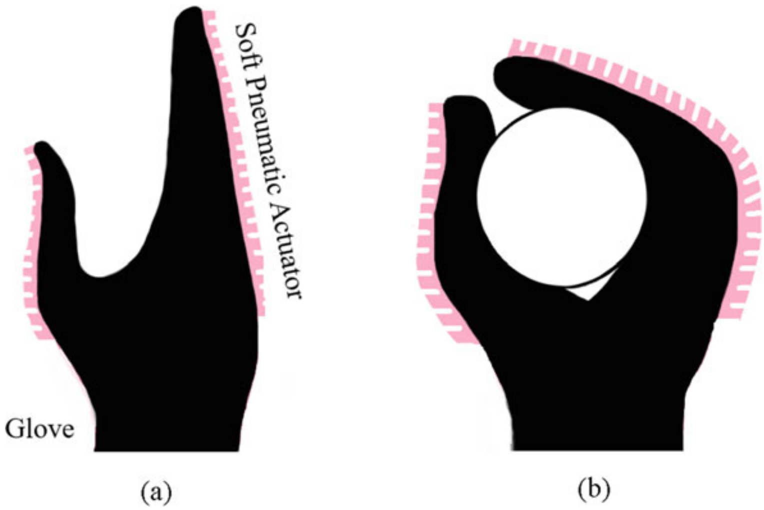

Fig. 1 Glove design for hand rehabilitation where the hand is in the open state (**a**) and close state (**b**) when grasping object

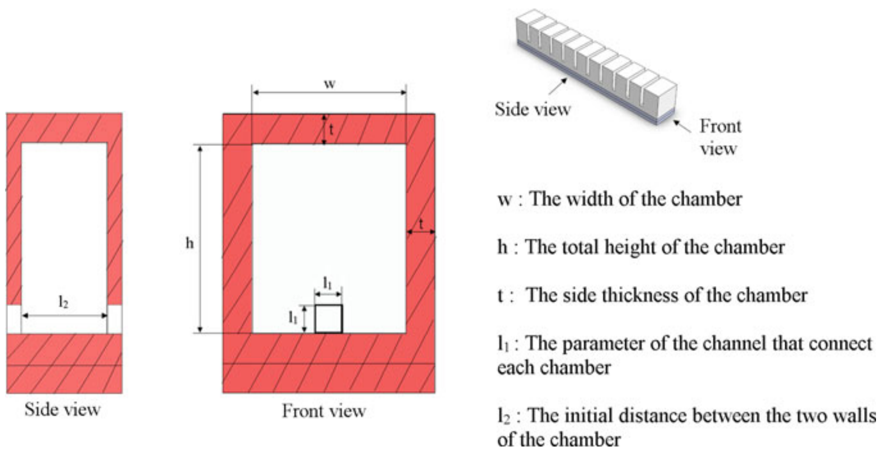

Fig. 2 The cross-sectional geometries of one chamber with the listed parameters (The left and right wall thickness of the side view are not considered in the model)

$\varepsilon(\sigma_x)$ is assumed to be the strain function of stress obtained by data extracted from the inside walls of the actuator modelling by FEM. The stress–strain results are modified by using Excel to get the function. Because the resulting strain_x is a nonlinear function of the induced stresses, we used a fourth polynomial fitting function to express the relationship between stress (σ_x) and strain (ε_x) with data extracted from Abaqus by applying 9 kPa pressure to the actuator. Due to system configuration, stress–strain data of the entire element could not be obtained. Therefore, the stress–strain result was computed by taking the average number of three chambers, including the first, middle, and the last.

$$\varepsilon(\sigma_x) = -332,663\sigma_x^4 + 25,960\sigma_x^3 - 616.03\sigma_x^2 + 8.4002\sigma_x - 0.002 \quad (2)$$

According to the axial direction, the axial deformation of the individual chamber, resulting in the change of shape when inflating:

$$D_x = \mathrm{l}_2\varepsilon(\sigma_x) \quad (3)$$

where l_2 is the distance between two walls before inflating.

Due to the restriction of the inextensible bottom layer (a paper which embedded in two-layer of elastomer), the soft actuator goes through bending deformation which creates the bending axis. Thus, the bending angle (θ) of the actuator could be calculated by integrating all the bending angles of the chambers:

$$\theta = 2n\tan^{-1}\frac{l_2\varepsilon x(\sigma x)}{2h} \quad (4)$$

where n is the number of channels. And the bending radius of the actuator:

$$\mathrm{R} = \mathrm{L} \quad (5)$$

With L is the total length of the actuator.

The design structures and parameters are modified from Soft Robotic Toolkit [12], which applied PneuNet principle of operation. This design is typical pneumatic networks that can only bend in one direction under pressurization. The fabrication of soft pneumatic actuator consists of an extensible top layer (main body) and inextensible bottom layer (Fig. 3a) which are cast separately with different mold design and then combined, including main body, which is the extensible layer of pneumatic actuator, expands when inflated. The main body is cast in the two-part mold shown in Fig. 3c. It has the gap between the inside walls, and the thickness of each chamber walls are thinner than the gap between the top wall and the inside wall; bottom layer, which is an inextensible layer, contains a paper layer which embedded in the elastomer.

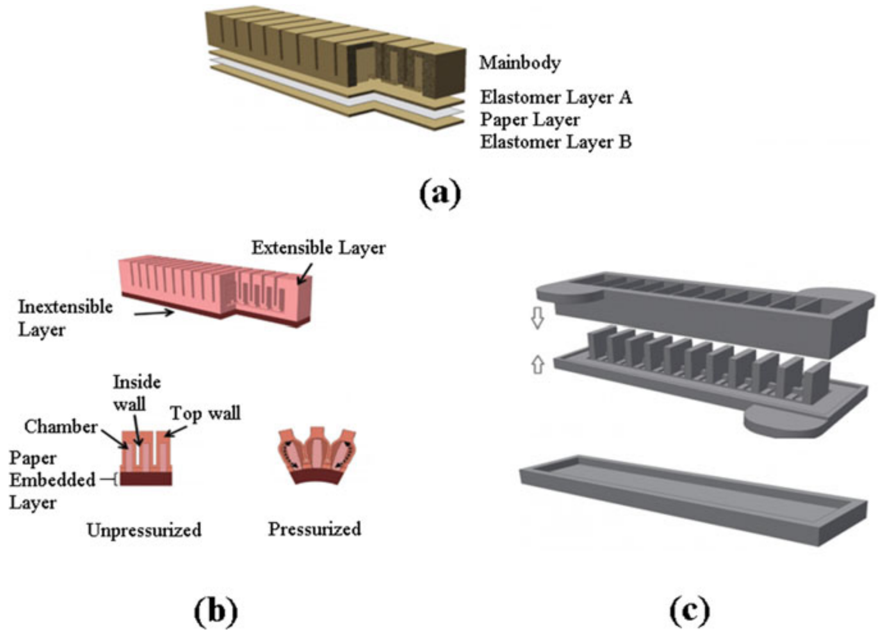

Fig. 3 Design structures of the soft pneumatic actuator [12]. An overview of design (**a**); Crosssectional view (**b**); Mold design to cast the actuator (**c**)

3 Results and Discussion

3.1 Mold Design

The solid model of mold design was carried out by using CAD through SolidWorks (SolidWorks.2018.SP2.0.Premium, Dassault Systèmes, French). The mold was made by 3D printing (from IN3DPLUS Co. Ltd) (see Fig. 4).

3.2 Simulation and Actual Results

The simulation software that we used is Abaqus (Abaqus 2017; SIMULIA Inc., France).

In the simulation, Ecoflex™ 00-50 (Smooth-On Inc., Macungie, Pennsylvania, USA) was set as the material properties. Due to the lack of equipment for fabricating the tensile test samples to find the best-fit material model, the mechanical properties using for simulation are implemented from Soft Robotic Toolkit [12] and Kulkarni [13]. Therefore, A reduced polynomial model (Yeoh) with coefficients of the fitted material models for Ecoflex series ($C10 = 1.27 \times 10^{-2}$; $C20 = 4.23 \times 10^{-4}$) and a

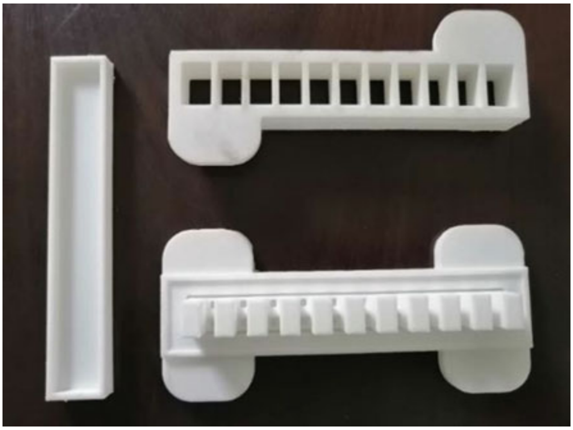

Fig. 4 Mold design by 3D printing

Young's Modulus with parameters for inextensible paper layer was used to build the properties of the material. Ecoflex™ 00-50 was assigned to two bottom layers and the main body; Paper was assigned to the inextensible layer, as shown in Fig. 5.

We carried out some empirical tests to validate the results of modelling. In the real experiment, one end of the actuator was kept fix by hand as the boundary condition "ENCASTRE" used in FEM. When applying pressure, the inflation of the actuator was observed and photographed by a smartphone camera (see Fig. 6).

According to the literature review, we measured the trajectory of the tip by recording its actuation to estimate the bending curve of the actuator. The measurement method was proposed by Polygerinos et al. [6].

We used a smartphone camera (Huawei) and a tripod which ensure the camera perpendicular to the plane. The actuator was filmed from the side to observe its tip when inflation. We use the size of the A4 paper to address lens distortion, and a ruler was fixed beside the actuator. Then, MATLAB program was used for analyzing the bending curvature between FEM and proposed (see Fig. 7).

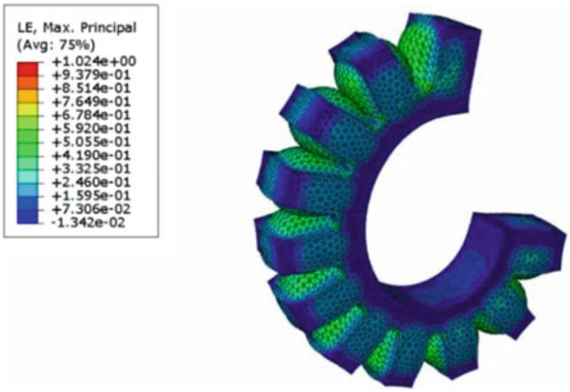

Fig. 5 The bending behavior of the soft pneumatic actuators

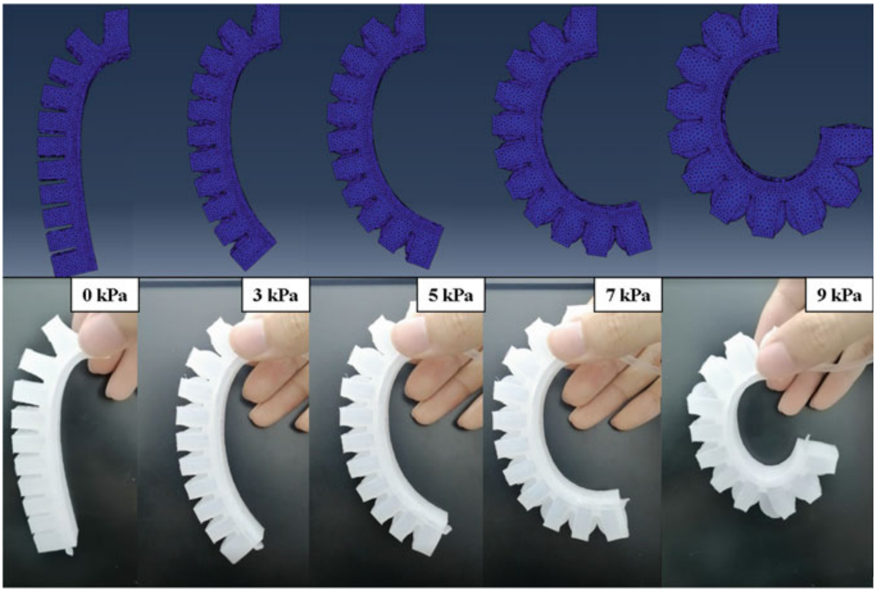

Fig. 6 Comparison between fabricated actuator and simulation model with the applied pressures are 0, 3, 5, 7, and 9 kPa, respectively

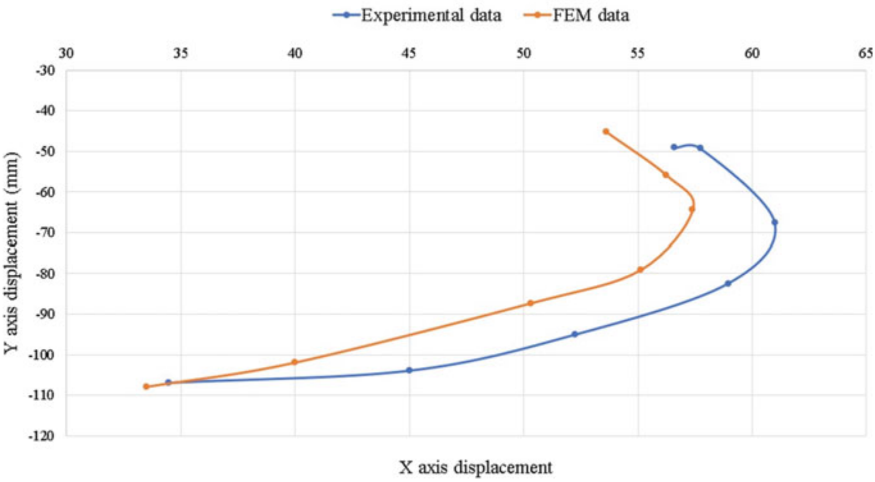

Fig. 7 Comparison of experimental bending curvature and FEM data when recording data of tip displacement

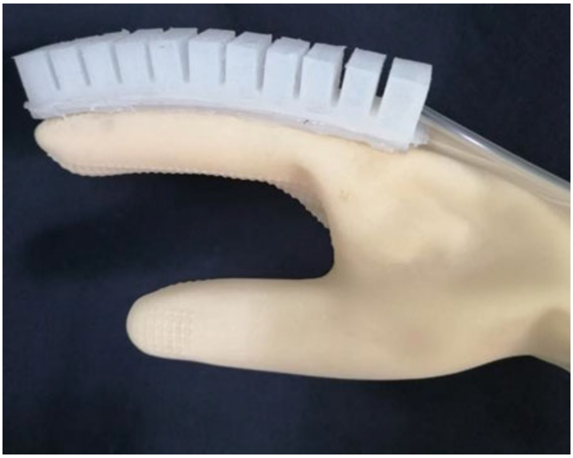

Fig. 8 A prototype of soft hand rehabilitation

3.3 Glove Design for Hand Rehabilitation

With the actuators attached on the top of each finger of the glove, its configuration is completely fitting to the human hand. Elastic fabric (vinyl chloride) was the main material for manufacturing glove. In this section, we demonstrated one of the applications of the soft pneumatic actuator, which is used in rehabilitation glove. As shown in Fig. 8, by placing the soft actuator on the top of the glove's finger, it allows greater concordance at all bending angles of the joints.

Due to the design requirement of rehabilitation glove, the output force of the actuator must be substantial to bend and actuate the finger joint effectively. Besides, the ability of glove should be tested for grasping with various objects in size and stiffness to control internal pressure and exert forces in different patients due to the complications of their diseases.

4 Conclusion

The objective of this work was to make a prototype robotic glove for hand rehabilitation therapies. The concept of inflating a soft pneumatic actuator to generate a guideline and help to develop this field in Vietnam. We presented the design, fabrication, and empirical tests of the soft pneumatic actuator. The finger design is referenced on the principle of the soft pneumatic actuator of but applied low-cost elastomer (Ecoflex™ 00-50). The FEM simulation results are used to compare with reality actuator to demonstrate that the mathematical model could be used to optimize the design and predict the behavior of soft actuators. In conclusion, the analysis of soft pneumatic actuator in this paper can be useful for future design and application of a soft biomedical glove for hand rehabilitation in the future.

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Conflicts of Interest The authors have no conflict of interest to declare.

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