Exploring solutions to assist finger rehabilitation with flexibility

Jihe He*

St. Ignatius College Preparatory, San Francisco, USA

*Corresponding author e-mail: hzhe_wjdi@163.com

Abstract. Motivated by the need to help those people whose hands and fingers are incapacitated due to injuries or birth defects, the curved-type pneumatic artificial rubber muscle is discussed in this paper, which is shown to be more flexible and convenient than traditional motor-driven soft robotic devices for hand rehabilitation and assistance if designed correctly. When people are injured, their finger joints become stiff and not be able to fully flex. Thus, an assisting device is needed. Machine-based hand exoskeleton for rehabilitation uses hardware and hard components, which carries the risk of furthering the injuries when the exoskeleton breaks or exceeds its driving capacity. In comparison, air-pneumatics driven hand rehabilitation device composed of flexible air muscle not only curves smoother, but also weighs lighter and can be designed as a carry-on, providing safety, utility, and comfortability. Several experiments and researches were run to determine the best structure and air-pressure to suit such purposes. Instead of the traditional button-pressing panel, Neuron-Muscular Transmission (NMT) - a detectable chemical signal - is used to activate the inflation and deflation of the device, therefore making the device thought-driven. In the end, Flexible Pneumatic System (FPS) is created to improve hand rehabilitation and supportive exoskeleton devices.

1. Introduction

Today, people use their fingers in a lot of areas, and it’s rather common to get a finger/hand-related injuries due to physical activities or diseases. In this case, hand supporting exoskeleton and rehabilitation device is necessary to aid such recovery. According to studies [1], hand injuries are often resulted from mechanical works and driving clashes in which the victims need their hands to do their jobs: Country’s economy is driven by those working class; hand injuries would ruin their employment and downgrade their social status, therefore causing a loss of economy and reduction in the quality of life. Based on the HISS data, zone 3 gets injured most of the time, with zone 2 coming in second for a hand injury. Those two regions are Metacarpals and Phalanges which contain joints. As finger sections’ bending motion at joints is required for the majority of people’s daily actions.
Therefore, it is needed to invent a carryable and effective hand device for rehabilitation/training and grip assistance, and one suitable solution is pneumatic air muscle. McKibben type rubber is not used because curving motion is required instead of linear motion. There are two types of curving air muscle.

First one [2] consists of an internal inflatable device, a bottom stabilizer, and may or may not add a wall restrictor mesh. This structure presented below is made of a rubber tube, fiber bellows, and a fiber tape. When the air is injected into the rubber tube, the rubber tube expands.

Second one [3] is made of several connecting airbags in whatever shape uniformly with edge restrictions. This structure presented below consists of several circular airbags made of textiles with a thick restrictor layer on its outermost edge, making the bag’s expansion direction only to the front and back. This design not only weighs lighter than the first one, but also can adapt to both linear and curving motion.
2. Materials and Methods
The overall goal of this project is to create a pneumatic muscle that when pressured with air can curve and have enough force to have the object attached to it to also curve. Several structures and manufacture method were tested, and they are (all their length are finger-lengthed):

2.1. One time mold injection with inner wax mold to shape cavity
Ten airbags (with cavity of its shape) with 1 mm gap in between connected to each other by a small 2.5 mm diameter circular airway on the bottom of each airbag. Thickness of the wall is 2 mm throughout. The extrusion tube to connect to the air tube is 4.5 mm out and 3.5 mm in 1 mm thickness. The purpose is to have the top airbag portion expanding, pushing each other and causing the structure to curve.

![Figure 4](image)

Figure 4. Two or more references.

A separate box mold to create the interior wax mold for structure’s cavity was created. It consists of three layers and the wax mold would be made facing up. Based on the design, ten wax mold are created and pierced by a wooden stick of 2.5 mm diameter.

![Figure 5](image)

Figure 5. Two or more references.

After eyeing the spacing and fixing the wax mold onto the stick with wax fixation, the compound is carefully enclosed by three pieces of outer structural mold and secured with screws.

![Figure 6](image)

Figure 6. Two or more references.

It’s not working. When air is injected into the structure, the wall quick creates air holes and bursts due to the weak combination of soft silicone, thin wall, and many air bubbles. The piece itself is also very easy to break and cannot curve at all due to that fact.
2.2. Two time mold injection with inner 3D printed mold to shape cavity
A semi-circle cylinder airbag with a semi-circle cylindrical cavity made with soft silicone. One of the ends and the bottom rectangular layer is thickened with hard silicone, making the top semi-circle layer thinner and more flexible than the bottom. The purpose is to have the top portion expanding while the bottom portion is restricted, causing the top portion to push the bottom and thus curving the structure.

![Figure 7](image1.png)

Figure 7. Two or more references.

The mold has three 3D-printed layers - a semi-circle cylindrical shelled outer structural layer, a semi-circle cylindrical solid inner cavity layer with a flat platform at the end, and a rectangular top thin enclosing layer. All three layers are wiped with Vaseline to ensure easier demolding. The final product - silicone air muscle with cavity (a long strip of semi-circle airbag in this case) - is completed after demolding.

2.3. Split type mold injection with layered acrylic board mold (laser cutting + fabric)
A finger-like shape - a rectangular prism with a semi-circle cylinder attached at one end. It is seven layers thick (each layer is 2.52 mm thick) with a four layers high multi-cross shaped cavity from the bottom. The whole bottom is sealed with a piece of rag cloth coated with silicone and cut to the fitting shape. The purpose is to have the small airspace inside expand throughout the airway, pushing each other and causing the structure to curve.

![Figure 8](image2.png)

Figure 8. Two or more references.

2.4. Split type mold injection with full 3D printed mold [inside & outside] (fabric)
Ten triangular shaped airbags with triangular cavity, with 1 mm distance between each of them, connected by a 2.5 mm diameter airway… (HIGHLY SIMILAR TO THE FIRST ONE but using a different manufacturing process instead of wax one-bodied).

![Figure 9](image3.png)

Figure 9. Two or more references.
Vaseline wipe four pieces of mold - two half pieces combine to make one outer mold with the top side having the outermost shape of the muscle removed inwardly and opened up, with locking holes around the top surface’s edge; one piece of solid cavity mold shaped like the interior cavity of the muscle (airbag + airway) with keys around its top surface; and one piece of top flattening mold that presses against all exposing top surfaces, pushing out the excess content and making sure the contacting area with cloth is as smooth as possible.

![Image](image1)

**Figure 10.** Two or more references.

(TRIANGLE): It works very well. Although there are tiny air holes created from the air bubble, they can be easily patched due to the hardness of the hard silicone.

(TRAPEZOID): This final method created the perfect pneumatic muscle structure and trapezoid shape airbags are able to hold more air pressure, making this design capable of curving more than a human finger’s curving angle while remains in shape and doesn’t break or crack. It also gives a lot of driving force to bend the finger since larger airbags pushing each other generate more power than other designs.

![Image](image2)

**Figure 11.** Two or more references.

(BULLET): made with liquid medium silicone and the same improved procedure as the trapezoid prototype. Almost as good but curves at a lesser angle than the trapezoid structure due to its bullet-shape airbags having smaller volume than trapezoid-shape airbags.

![Image](image3)

**Figure 12.** Two or more references.
3. **The overall structure**

The final project is composed of the following: On one side - backhand portion- of the fiber cloth glove, a strip of curving air muscle is glued and silicone to each finger. Then, five separate air tubes are each inserted into and glued to each of the air muscle, and tubes’ length stretched entire arm’s length, went around the back shoulder, and finished diagonally, connecting to the central box of the main control system at waist level.

![Image](image.png)

**Figure 13.** Two or more references.

3.1. **Connection of whole air channel**

The connection of the whole air channel is as shown in the following figure. The air source is connected to the convergence plate through an air pipe and distributed to five electromagnetic valves via the convergence plate, so that the five pneumatic muscles are independently controlled respectively by controlling the electromagnetic valve, and finally the action of the fingers can be controlled.

![Diagram](diagram.png)

**Figure 14.** Two or more references.

4. **Experiments**

4.1. **Material’s flexibility**

The purpose of the experiment is to find out the best material for the purpose of this project, regarding to what degree the pneumatic muscle is able to curve under each of the three types of silicone: HY-T05 (soft), HY-T10 (medium), and HY-E620 (hard). A protractor image is printed on a piece of paper and taped onto a brown cardboard for background setting and flatness. Then, each time, the end of the muscle where the air tube enters is placed on the center of the protractor, and the air is injected into the muscle and the muscle’s curving angle degree is measured based on the result shown on the protractor. Same shape of the muscle and the same air pressure are applied for this experiment.
Table 1. Quantitative data.

| Curing angle | HY-T05 (soft) | HY-T10 (medium) | HY-E620 (hard) |
|--------------|---------------|-----------------|---------------|
| 110          | 120           | 40              |

4.2. Muscle design’s Strength and Flexibility

The purpose of this experiment is to find out the best muscle design, creation method, and shape for the purpose of this project, regarding the flexibility and strength to bend fingers for each of the six designs including their method of creation. The same method for measuring the material’s flexibility and the protractor paper are used for each structure; it is then placed under a finger to determine the amount of driving force it gives to bend the finger. Same material of the muscle and the same air pressure are applied for this experiment.

Table 2. Quantitative and qualitative data.

| Curving angle | #1: upside down trapezoid | #2: semi-circle | #3: finger shape | #4: triangle | #4: normal trapezoid | #4: bullet shape |
|---------------|--------------------------|-----------------|-----------------|--------------|---------------------|----------------|
| Finger-bending force | Dig not work | 115 | 50 | 45 | 120 | 110 |
| Did not work | Medium | Medium | High | High | High |

To conclude, #1 upside down trapezoid shape is immediately excluded due to its inability to function. #3 finger shape and #4 triangle are excluded next due to their weak bending angle (more upward means it’s curving least effective) resulted from their little airbag space. Next, #2 semi-circle shape is outcompeted by #4 normal trapezoid shape and bullet shape due to its weaker curving angle (more outward means it’s curving less effective, while more inward means it’s curving most effective, so 110 degrees in this case is better than 115 degrees) and finger-bending force (high > medium). Therefore, Split type mold injection with full 3D printed mold [inside & outside] (fabric) [normal trapezoid] is considered to be the best manufacturing method and shape of design for the pneumatic muscle due to its strong finger bending force and best curving degree.

5. Conclusion

After the prototype for this device is finished, the experiment is successful in testing the device’s assistance in the fluidity of the basic finger movement. The summary is as follows:

1) Pneumatic soft muscle hand rehabilitation device, as tested, can increase the fluidity of finger movement, speeding up the process of regaining finger flexibility for the user at the early stages of rehabilitation.

2) Hand rehabilitation device stimulates the muscle movement smoothly with enough external force, can assist the user in grabbing items as an exoskeleton.

3) Hand rehabilitation device operates in a good condition, is more convenient and efficient to use, and is easier to be familiarized by the user

4) Hand rehabilitation device has a stable structure, high reliability, and good safety measures. The soft muscles form a natural curve for the joints to follow.

Aspects found during the manufacturing and experimentation that could be improved:

1) Can add neuromuscular transmitter (NMT) in the future to provide feedback on the progress of muscle recovery exercise, made it possible to facilitate the rehabilitation process automatically, no need for human instruction and control.

2) While using it, it is found that the over inflation of the airbags might cause them to pop since the different material thickness at different regions cannot hold too much air pressures. It is possible to
add an outside protect layer as a structural frame to prevent the airbags from over expanding while maintaining pressure.

3) The glove has to be skin tight in order for the airbags to be most effective, yet it takes quite an effort to put the device on. For a stretchable material like cloth, gluing the airbags on will take away the flexible aspects of the glove. A better way of attaching the airbags tightly to the glove surface must be considered, such as sewing, etc.

References
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