Proceedings of 2015 IEEE
International Conference on Mechatronics and Automation
August 2 - 5, Beijing, China

Soft Actuator for Hand Rehabilitation

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***Abstract* – As we all know, rigid structure is the universal form of robots. They can be controlled accurately, but are not suitable enough for applying in rehabilitation, especially for hands. Human's hands have some complicated patterns of movement and narrow joint range of motion, so rigid accessory equipment may cause secondary injury. For the purpose of avoiding this potential risk, the idea of applying soft structure to hand rehabilitation robot is presented in this paper. The soft robot is a new research direction in the field of robot industry, especially in rehabilitation. The soft actuator we presented is made of liquid silicone and thread, and can be tied to the back of human's hands. When it is inflated or deflated, a bending and stretching motion of hands follow with the deformation of soft actuators. It works by deforming repeatedly. The soft actuator has some advantages such as portable, lightweight, low-cost, safe, low-impedance and so on. It works well by the cooperation of vacuum pump which can provide incessant air and solenoid valve which is used for reversing. In the whole system, force sensing resistor and bending sensor are used in the experiments. In order to prove that the soft actuator can work smoothly, we had a test to explore the relationship between air inflow and bending angle. The result that their relationship is close to a straight line means controlling easily and working well. Beacons of these advantages the soft robots have, a wide application prospect in rehabilitation or other fields is available.**

Index Terms-Rehabilitation, Soft Actuator, Portable System

I. INTRODUCTION

Data from the World Health Organization (W.H.O) show that the stroke has an increasing incidence as one of the serious diseases threatening the health of human being. Stroke has four characteristics: high incidence, high mortality, high disability and high recurrence [1]. More than 11.67 million patients in a group of people over 40 years old still suffer from stroke in China. Over 2 million people are added to this group each year. The annual growth rate of incidence of stroke is 13.19%, and nearly 60~75% of them can survive [2]. It is very common to patients who lose their function ability of hand after stroke, which can greatly inhibit activities of daily living (ADL) and considerably reduce one's quality of life [3]. This supplies us a promising market of rehabilitation equipment.

There are many research institutions concentrate on developing robots to help people who are hemiplegic after stroke, especially for hand rehabilitation. The designs of the hand rehabilitation robot are basically exoskeleton devices, which can be well working by fixing on the disabled hand. Continuous passive motion (CPM) devices are considered to be a good mechanism to the therapist, especially in various joint rehabilitation procedures such as hand rehabilitation [4].These devices can be actuated by motor, pneumatic muscle, cylinder, hydraulic system, or shape memory alloy (SMA) [5-7]. All the devices have their own advantages, but rigid devices is high-impedance and high weight, they are discommodious for patients and may do harm to their hands once again. In order to be more securer and portable for patients, we provide a new type of soft hand rehabilitation robot.

Soft robot research has a short history. It is a branch field of bio-robot research which is relatively new. There is no remarkable difference between soft robot and bio-robot. Comparatively, soft robots use less of rigid constructions. Bionics was founded in 1960[8]. From then on, more and more people begin to pay attention to bio-robot, but in resent ten years, the concept of soft robot has been put forward. Chembots was a kind of soft robot based on materials chemistry and robotology made by DARPA in 2007. It can refactor its form and size. In 2009, the octopus project was started. It was funded by five countries and mainly aimed at study the actuator and sensor in it [9]. There are some quintessential soft robots such as the robot made by Barry A. Trimmer from Tufts University [10], the Blob bot made by iRobot [11], the Soft Robot used for gait rehabilitation towards rodents [12], Pneu-net robot made by Harvard University in 2014 [13] and so on. At the beginning of exploring stage of soft robot, no mature work has been worked out yet, especially in the field of rehabilitation. In this paper, a soft actuator is presented to solve the problems which the rigid structures have. The process of design and manufacture of the actuator is reduced, and some experiments are developed to prove that the design is feasible.

II. SYSTEM STRUCTURE

A. The rehabilitation system structure

The whole rehabilitation system contains five units: pump unit, valve unit, control unit, sensor unit and soft actuator. The schematic diagram is show in Fig 1.

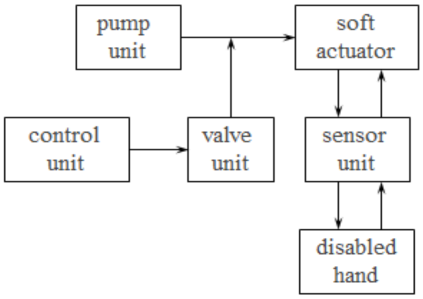
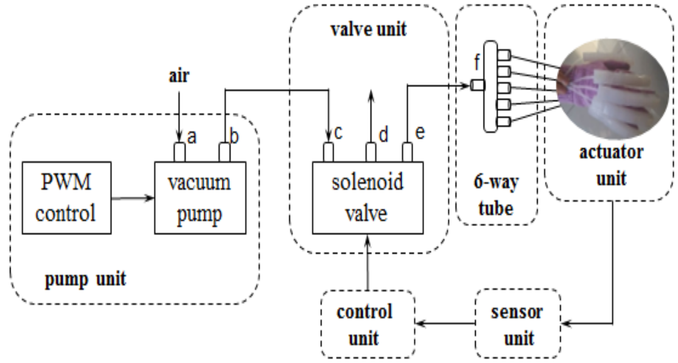


Fig.1 Schematic diagram of the system component

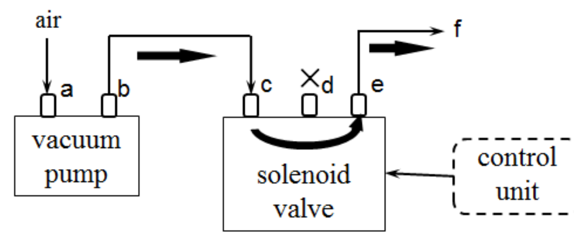
In this system, the pump unit is used for supplying air that the actuators need for deformation. The pump we use is a kind of minipump (KVP04) made by Kamoer. It is speed-adjustable, portable and lightweight; besides, intermittent positive negative pressure ventilation (IPNPV) is available. The speed of pump can be adjusted by PWM generator. A critical component of the valve unit is a solenoid valve. It is a two-position three-way reversing valve, which can change the direction of air flow without changing the circuit of the pump. Air in the loop of the system can be let out in the atmosphere directly, so the rehabilitation system is clean and environment friendly. The actuator unit contains five bio-fingers used for driving disabled fingers to bend. It is hollow and fiber reinforced, which we will discuss later. The sensor unit is used for monitoring the deformation and the pressure between actuators and fingers. The control unit is used for control the air flow and the aerating rate. By inflating/deflating repeatedly, disabled fingers become deformed following the actuators. After repeated training, the fingers can be retrained. Then we can achieve our aim of rehabilitation.

B. Schematic of the system's working principle

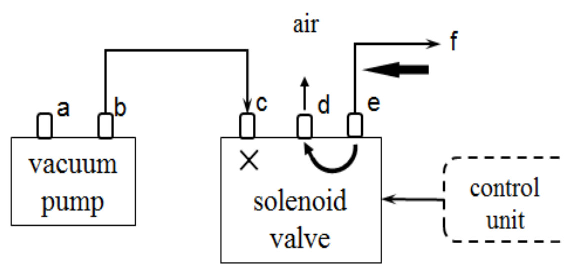
Deforming smoothly for the soft actuators is very important in the process of rehabilitation. For the purpose of getting better training effect, the working process is designed in Fig.2. The pump is portable and compact, which can work smoothly just in air. When we switch on the pump, fresh air is inhaled in the pump, and then delivered in solenoid valve after being compressed. In the process of inflating, the port-d of the solenoid valve is closed, the compressed air come from port-b flow to the port-e, then to the soft actuator, and the process show in Fig.2 (b). In the process of deflating, the port-d is opened and port-c is closed. Based on the pressure difference, pressure of port-d is lower than port-e, so the airflow direction is like (c) in Fig.2. During working, sensors are used to monitor the real-time status and to control the whole system easily, and to avoid excessive deformation of the actuator. A 6-way tube which can divide one gas circuit into five connect the valve unit and the performing unit. This way of connection has both advantages and disadvantages. Several pumps and solenoid valves can be omitted which can lower the manufacturing cost. At the same time, the working models are reduced relatively for the actuator unit.



(a) Schematic of the whole system



(b) The process of inflating



(C) The process of deflating

Fig.2 Mechanism for working of the system components

C. Sensor unit

Two kinds of sensors are used in the system. Bending sensor is used for measuring the deformation angle and force sensing resistor is used for monitoring pressure between soft actuators and corresponding fingers. The force sensing resistor (FSR402) is a kind of filmy-resistance-type sensor made by Interlink Electronics. Its working principle is transform the pressure adding on the membrane into the change of resistance. It is fixed on the phalanges of fingers covered by soft actuators. When the actuator is inflated, the actuator bends and starts to squeeze the phalanges of fingers, then we can monitor stress conditions that patients are bearing. This helps us insure the pressure is acceptable and safe for fingers. The bending sensor (FLX-03, made by Spectro come from Germany) is mainly used for measuring the relationship of air inflow and bending angle, with the purpose of controlling the switching time. The two kinds of sensors are shown in Fig 3 (a) and (b).

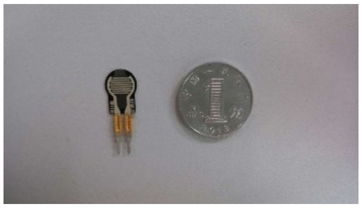


Fig.3 (a) Force sensing resistor

Fig.3 (b) Bending sensor

Ⅲ. DESIGN AND MANUFACTURE

A. Dimensional design of single actuator

Based on the results of data statistics towards to human's hands, we get the length range of finger phalanx and the diameter of finger joint correspondingly of a healthy people. The data are summarized in table1 [14]. According to the data, we choose the average length of middle finger as our standard. Furthermore, there should be another length about 30 millimetres are preseted for assembling. Finally, we finished one single actuator designing with 130 millimetres in length and 18 millimetres in width. The CATIA design of single finger part is shown in Fig.4.

TABLE 1
Length range of finger phalanx and the diameter of finger joint of healthy people

	MCP Joint	Proximal Phalanx	PIP Joint	Middle Phalanx	DIP Joint	Distal Phalanx
Thumb	26~29	45~55	16~18		14~17	28~33
Index Finger	23~26	43~50	15~17	24~30	12~15	23~26
Middle Finger	24~27	44~51	16~18	25~31	13~16	24~27
Ring Finger	23~26	43~50	15~17	24~30	12~15	23~26
Little Finger	21~23	37~42	12~15	23~26	11~10	21~24

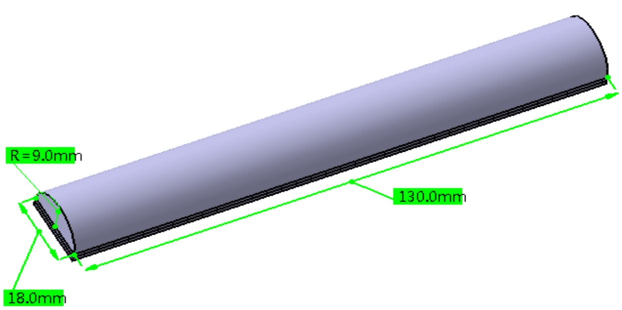


Fig.4 Design of dimension and shape

B. Internal geometry design

In order to fabricate a better actuator, we designed several shapes for simulation. Internal structure is the key of success. The actuator is hollow, which can be filled with air. It has a multi-cavity structure inside. After multiple simulating, we got the appropriate space between two cavities. The CATIA design of primary internal geometry is shown in Fig.5, the semicircular channel is used for airiness.

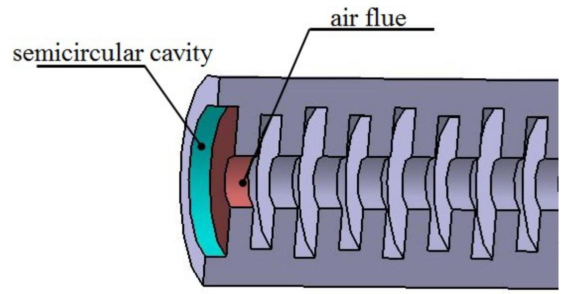


Fig.5 Internal geometry of multi-cavity soft actuator

C. Simulation in different structures

Before the process of manufacture, we do some simulations to avoid unnecessary mistakes. In our research, we use liquid silicone (Ecoflex 30) made by Smooth-On, which is a non-linear superelastic material. The software we use to do FEM analysis is ABAQUS 6.13. It is a powerful tool which is good at non-linear analysis. In order to simulate the deformation, some parameters of the material are tested. Silicone is a kind of hyper-elastic stuff. Based on the material test made by a student come from the Ohio State University, we get some data ready-made. After material test, he obtained a stress-strain curve. As we use the same stuff as they do, so we can use the data they had got yet. The characteristic of the Ecoflex 30 material can be described by a Yeoh model in equation 1, and the parameters in it are needed in ABAQUS.

$$U = \sum_{i=1}^{n} C_i\,(I_i - 3)^i \qquad (1)$$

In this equation, U means the strain energy of the material, the C_i means material constant, the I_i means Cauchy's deformation tensor invariant. After test, the Yeoh model coefficients were determined as C_1=0.008, C2=0.00009[15]. There are some key things we should pay attention to during the process of simulation. At the step of edit material, we choose hyperelastic in mechanical setting, the strain energy potential set as Yeoh, the Input source set as coefficients, and then the coefficients mentioned above can be used.

Since there are two kinds of stuffs: silicone is used for forming integral structure and paper is used for making restrictive layer. The sections in ABAQUS should be set separately in the step of mesh. In the edit step session, you can choose a smaller value compared with the default at the incrementation option. In a general way, reducing just one order of magnitude is feasible. Too much modification would lead to non-convergent. Several simulation results at the same load condition but with different internal geometry are shown in Fig.6. In picture (a), we can see that the soft actuator bend very well. It can bend nearly 180 degrees at a low pressure about 0.01 MPa, which is enough for disabled fingers in rehabilitation. This structure has a regular internal geometry.

We can see that it has an obvious deformation. In order to reduce the level of deformation, some measures are taken which we will discuss later.

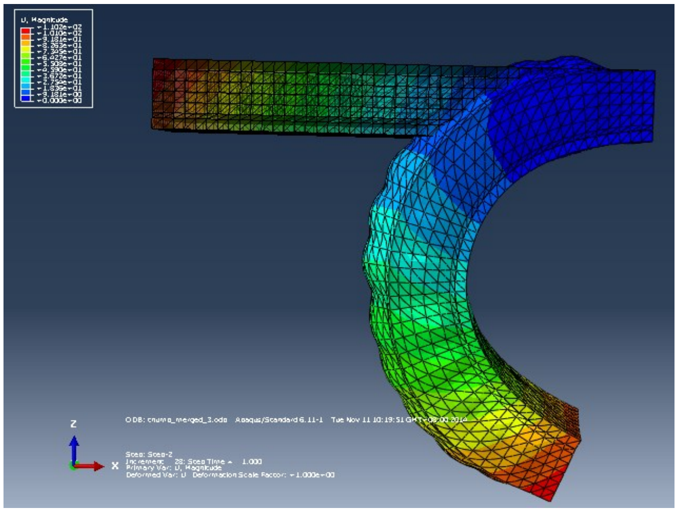


Fig.6 (a) Simulation results with a cuboid section

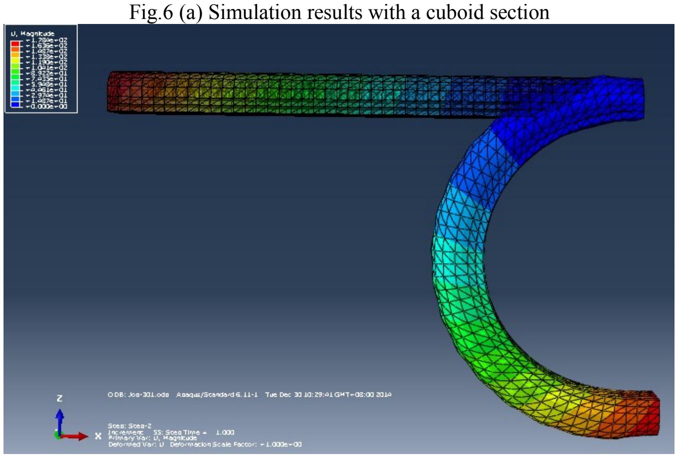


Fig.6 (b) Simulation results with a semicircular structure

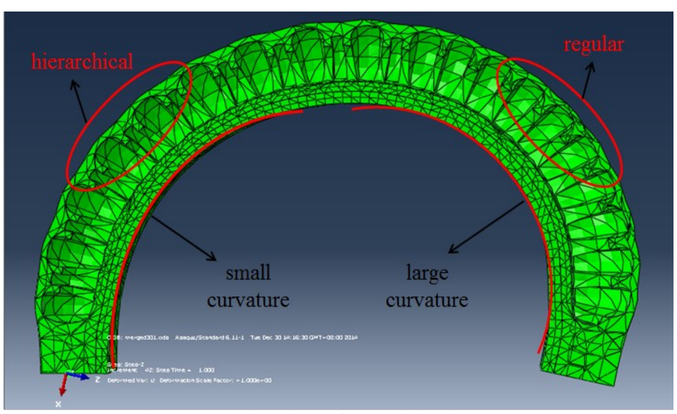


Fig.6 (c) Section view of a semicircular structure

Simulation (b) is the result of the improved structure, which substitute a semicircular structure for a cuboid section. It is obviously that the deformation becomes more uniform and beautiful. In the third picture of Fig.6, two kinds of internal geometry are simulated at the same time, not only can save time, but also is convenient for contrast. In the picture we can see that hierarchical structure has a smaller curvature than the regular one, which means that the regular structure is easier to deform than the hierarchical one. In other words, the regular structure need lower pressure to deform. This provide us ideas for specific design for multi-joint fingers.

D. Manufacture

The soft actuators presented in this paper are made by liquid silicone (Ecoflex 30). This material is made up of part A with part B. It will maintain liquid without either part of them. The silicone is nontoxic, so it can be operated without any safety measures. The specific steps are shown in the Fig.7. Firstly, we need to mix part A and part B together in the ratio of 1:1, and stir them adequately. In order to reduce bubbles in it, which can do harm to the quality of the actuator, the mixture needs to be stand for 5~10 minutes. Then pour the mixture into the mould made by 3D printing within thirty minutes before the silicone's fluidity get worse. The soft actuator can't be made by only one-step. It is coherent by three parts. Schematic is shown in Fig.8. The hollow layer has cavities inside, and the middle layer is used to seal it. This process contains two curing steps. Then pour enough silicone into the bottom mould with a nonelastic material such as a strip of glass fabric, which has a smaller size than the groove in the mould and be sure that the glass fabric is encapsulated by silicone. The reason we use two steps to seal the channel rather than use a thick layer by one step is that one-step forming has a bad performance, in other words, it is easy to be leaky and destroy the actuator. What calls for special attention is that the curing temperature should be maintained at room-temperature like 25 centigrade. Experiments proved that higher temperature lead to shorter forming time but bad quality, and lower temperature result in longer forming time but similar quality.

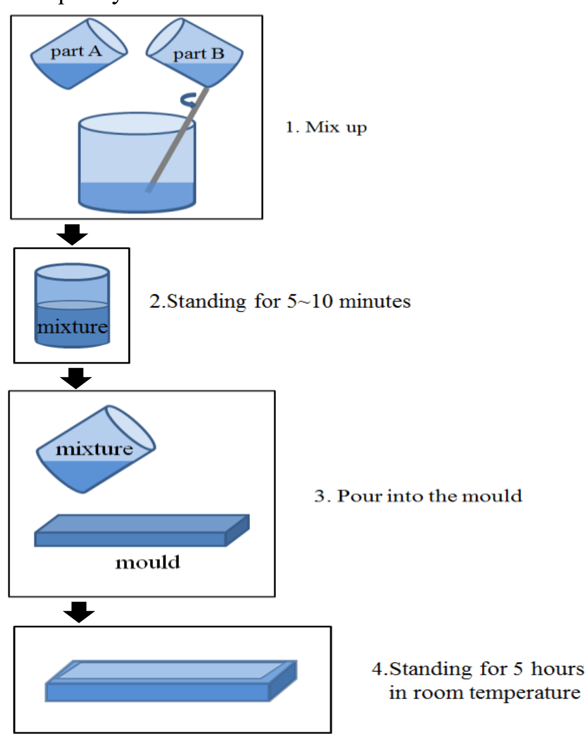


Fig.7 Manufacturing process

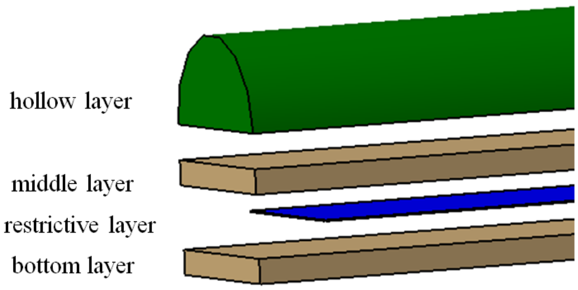
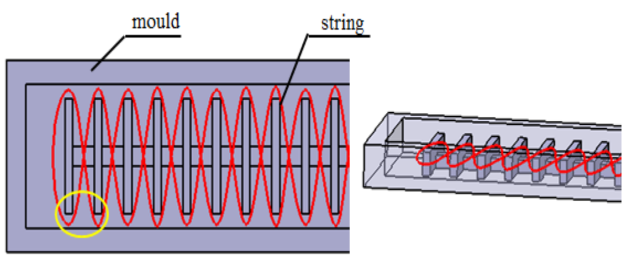


Fig.8 Schematic of actuator's form

IV. EXPERIMENTAL SETUPS

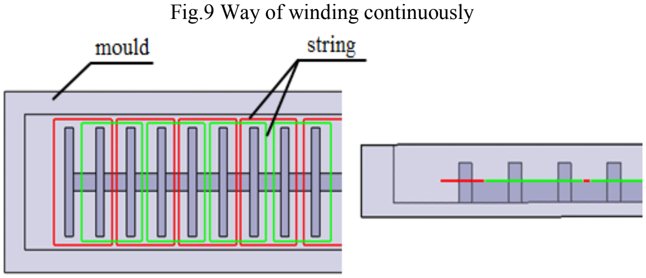
A. Fiber reinforced exploring

We mentioned a disadvantage in the simulation part that silicone-only structure is easy to be excessively deformed. In order to solve this problem, we explored several ways to limit the deformation. A very effective way is making it a fiber reinforced structure. Two ways of winding are shown in Fig.9 and Fig.10.



(a) Top view (b) Side view

Fig.9 Way of winding continuously



(a) Top view (b) Front view

Fig.10 Way of winding intermittently

The way of winding in Fig.9 is continuously. It means that the filament winding on the mould is integral, not being intercepted, and the beginning and the terminal are tied together. This twining way is easy to get, but there are some details need to notice. The winding should be neither too tight nor too loose. If it is tight enough, the string will separate itself from the silicone and stay with the mould. When it is too loose, the deformation will be ragged, so being symmetrical for the winding way is very important. In the Fig.10, both the red and green line represent independent winding. One cavity can be surrounded by one coil, but the winding are crossed with each other. Too loose or too tight is not allowed either. When we finished winding it, pour the silicone into the mould, during the period of curing, be sure that the string would not rise up to the surface of the silicone, which will lead to failure.

B. Experiment of inflating

To demonstrate that the actuator can be well working during the process of inflating, we designed a test like Fig.11. Air pressed in the actuator is quantitative. In order to control momentarily, we use injector replace the pump to supply compressed air. The bending sensor is stick to the actuator which side bend only. Arduino is used for programming and the computer is used for collecting data. The result is shown in Fig.12. We did three tests and the black curve is made on the average value of corresponding values. We can see that the three curves are close to the straight line. As the silicone is a non-linear material, this trend of deformation is satisfactory.

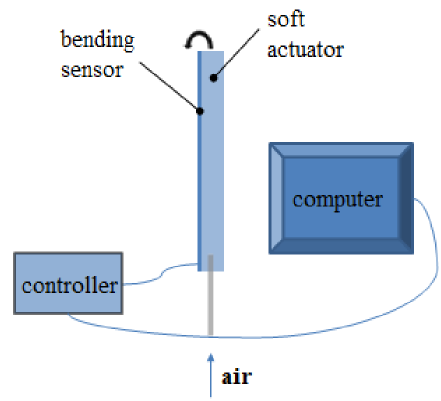


Fig.11 Schematic of test platform

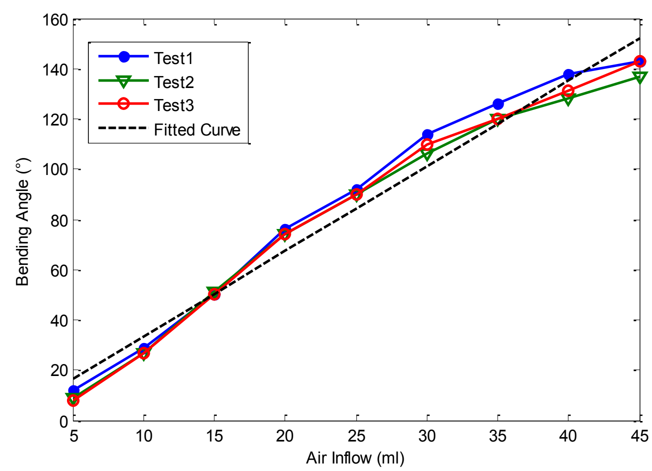


Fig.12 Relationship between air inflow and bending angle

C. Experimental platform

In order to test the feasibility of the system, we set up an experiment platform in Fig.13. It consists of pump, valve, PWM, tubes, actuators, controller and switch. Different level of deformation based on different internal design, just like the result on the left side of the picture. In this system, five actuators should be tied at the back of patients' fingers. When the actuators are inflated and start to curve, fingers bend by them. After multiple repeat, finger exercise can be realized. The actuators are not integrate from now on.

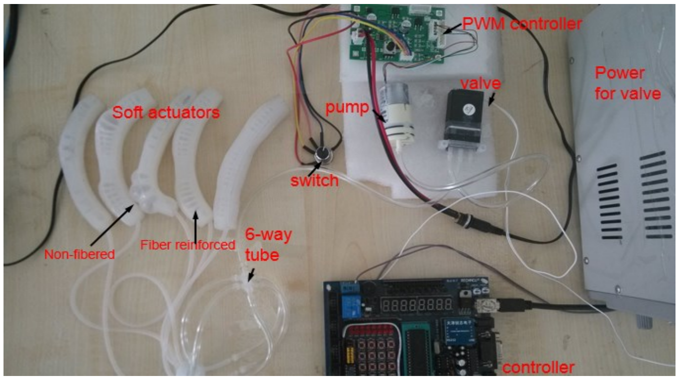


Fig.13 The whole system

V. CONCLUSION AND FUTURE WORK

In this paper, a new kind of actuator is proposed to help people retrain their disabled fingers. Soft robot is a new research direction of robot. Compared to the traditional rigid structure, soft form has some advantages such as lightweight, portable, low-cost, safe and so on. Few applications of soft robot are exist so far, especially for rehabilitation. So our research can provide a reference for soft robots' application and manufacture. Based on the test we did above, we draw the following conclusions:

1) Different internal design has different aalevel of deformation.

2) Fiber reinforced actuators have better effect than not reinforced ones.

3) The relationship of air inflow and bending angle is close to linear, which is good for control.

There are some disadvantages for the system. Only one pump is used to actuate five actuators at the same time, which can reduce the flexibility of each actuator. Multy-pump system increases the flexibility, but the weight and complexity are enhanced either.

In the future work, we will manufacture the second-generation soft actuator and integrate the actuators together. We will do some test to certify the reliability of the system. Pressure sensor will be added in it and the whole device will be portable.

VI. ACKNOWLEDGMENTS

This research is partly supported by Key Research Program of the Natural Science Foundation of Tianjin (13JCZDJC26200), and National High Tech. Research and Development Program of China (No.2015AA043202).

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