DESIGN OF WEARABLE PNEUMATIC HAND REHABILITATION DEVICE

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Abstract. This paper presents the design, fabrication and testing of a wearable hand rehabilitation device fabricated using flexible hoop-reinforced actuators, which can meet the safety and flexibility requirements of hand rehabilitation. Firstly, the influence of the geometrical parameters on the bending and force capability for the designed flexible actuator is analyzed by ABAQUS, and the best parameters are obtained. According to the length and width of each finger, all geometrical parameters of the actuators are determined. Then, actuator molds are created using 3D printer, and flexible actuators are fabricated with silicone rubber. A new flexible hoop-reinforced actuator is fabricated on the basis of improvement for the designed actuator. Its performance is measured by experiment. Finally, the wearable hand rehabilitation device is developed, and the basic motion control and experiments are carried out. The experimental results show that the hand rehabilitation device can meet the requirements of finger rehabilitation.

Keywords: pneumatic, flexible hoop-reinforced actuator, hand rehabilitation

INTRODUCTION

It is common for knuckle injuries caused by some disease, sports injury or traffic accident, which can weaken people's ability to have a normal life. Modern medicine supports that physical rehabilitation training plays a significant role in knuckle injury recovery and improvement [1]. Most of the traditional rehabilitation devices are driven by motors, which is easy to produce impact during the recovery process [2-5] and may cause secondary damage to the patient's fingers if the impact is serious. Moreover, these devices are bulky and inconvenient to wear.

Currently, pneumatic technology has been increasingly used in medical field and the flexible pneumatic actuators have gradually captured people's attention [6]. The flexible pneumatic actuators will contract [7], bend [8-11], twist [12] and move with multi degree of freedom [13] when pressurized. Integrating those flexible pneumatic actuators into hand rehabilitation devices are researched by an increasing number of research groups [14]. Some hand rehabilitation devices designed by flexible pneumatic actuators can produce bending motions [14-16] and have great flexibility.

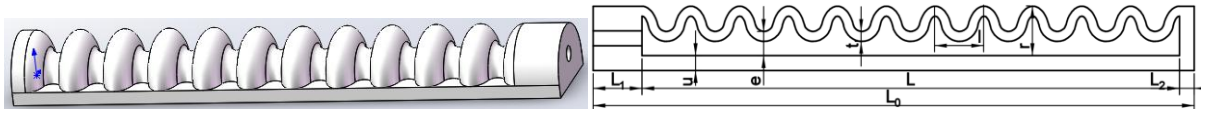
In this paper, a wearable hand rehabilitation device is developed that can make human fingers to generate bending motions. The effect of the geometrical parameters on the bending and force capability for the designed flexible actuator is analyzed by ABAQUS, and the best geometrical parameters are obtained. A new flexible hoop-reinforced actuator is fabricated on the basis of test and improvement for the designed flexible actuator. Its performance is measured by experiment. Finally, the wearable hand rehabilitation device is developed by athletic gloves and the finger flexible hoop-reinforced actuators. The experimental results show that the developed hand rehabilitation device can meet the requirements of finger rehabilitation training.

DESIGN OF FLEXIBLE PNEUMATIC ACUATOR

Definition of Geometrical Parameters

The shape of the designed flexible pneumatic actuator according to the width of the index finger is shown in Fig.1(a), whose upper side is wave shape. For the generic design of the actuators used in the hand rehabilitation device, the geometrical parameters are shown in Fig.1(b): the length of the proximal cap L_1, the length of the distal cap L_2, the length of the air chamber L, the length of the actuator L_0, the radius of the wave crest r, the radius of the wave valley e, the pitch l, the thickness of wave structure t, the thickness of bottom u. wave crest is a part of ellipse, and wave valley is a part of circle which is tangent to wave crest. For the human fingers, take L_1=10mm, L_2=3mm, a=6.5mm, b=3.5mm, l=r. The radius of the wave crest and the length of the air chamber of

the actuator are taken r=10mm and L=110mm according to the width and the length of human fingers when analyzing the effect of the geometrical parameters e, t, u on the bending and force performances.



(a) (b)

FIGURE 1. (a) Shape of the flexible pneumatic actuator. (b) Geometrical parameters of the actuator

Material Properties

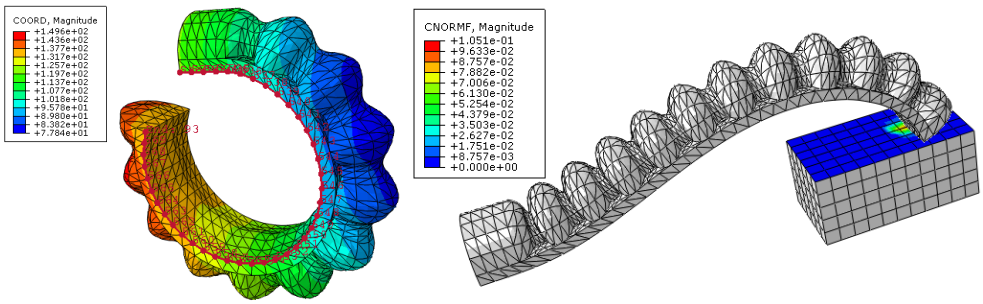
The flexible pneumatic actuators were fabricated by silicone with shore hardness A30 which is a kind of hyperelastic material. To get its accurate material properties, silicone samples were tested according to ASTM D638 at a rate of 500 mm/min for uniaxial tensile strength. A hyperelastic incompressible Yeoh material model with strain energy [17], $W=C_{10}(I_1-3)+C_{20}(I_1-3)^2+C_{30}(I_1-3)^3$, is used to capture the nonlinear material behavior of silicone. In particular, the material coefficients are C_{10}=0.18, C_{20}=0.0435, C_{30}=-0.0043 for silicone with shore hardness A30.

Finite Element Method

To get the best geometrical parameters for the designed flexible pneumatic actuator，the finite element model were developed by ABAQUS 6.14, which can get good simulation results of material nonlinearity and geometric nonlinearity when actuators is in large deformations. Yeoh model is used as the material properties of the actuator, and its coefficients are obtained by measurement. Density isn't set because the gravity of the actuator isn't taken into account. Nlgeom is set as on in the Step because of nonlinearity. The proximal cap of the actuator is completely fixed and the actuator is meshed using solid tetrahedral quadratic hybrid elements (ABAQUS element type C3D10H).

In bending model, the Pressure with the value of 120KPa was acted as Load at the chamber of the actuator. The node path was created in the bottom edge of the actuator(Fig.2(a)), then the curve of bending is obtained with the COORD handled by MATLAB.

In force model, the contact force is generated by making the distal cap of the actuator contact with a solid rectangular block which is simulated the force sensor [14]. The material of the solid rectangular block is modeled as linear elastic, with a Young's modulus of 7600MPa and a Poisson's ratio of 0.3. The contact force can be got by the maximum CNORMF (Fig.2(b)).

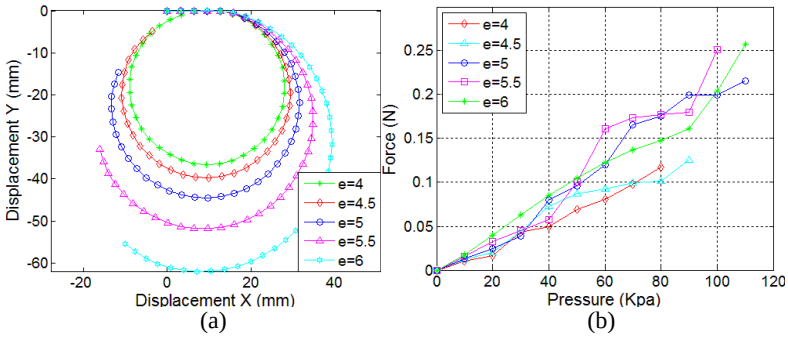


(a) (b)

FIGURE 2. (a) Bending model (b) Force model

Optimal Geometrical Parameters

In general, it is highly appropriate that the control variable method is used to analyze the influence of the geometrical parameters e, t, u. For the analysis of e, e is considered as variable with the value of 4, 4.5, 5, 5.5 and 6mm, t and u are taken as t=2mm, u=3mm. The results simulated by ABAQUS are shown in Fig.3. From Fig.3(a), the geometrical parameter of e has a considerable influence on bending, and the smaller the value of e, the more easily the actuator is to bend. The bending performance is better when the e has smaller value with 4, 4.5 and 5mm. From Fig.3(b), the contact force increases with the value of e when the pressure is below 20KPa. The force performance is better when the e has bigger value with 5, 5.5 and 6mm.



(a) (b)

FIGURE 3. Influence of *e* on actuator performance. (a) Comparison of bending trajectory. (b) Comparison of force.

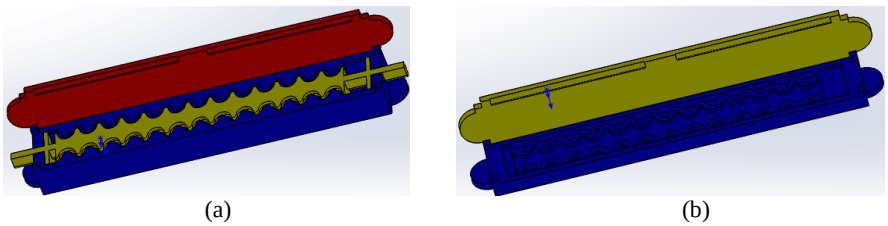
Combined with Fig.3(a) and (b), the value of *e* with 5mm is the optimal geometrical parameter. In the same way, the best *t* is 2mm and the best *u* is 3mm. The length and the value of *r* are defined by the length and the width of the four fingers. The width of index finger, middle finger and ring finger is considered as the same and the width of the little finger is 9/10 of the index finger. All geometrical parameters of each finger actuator are shown in Table.1.

TABLE 1. Parameters of each finger actuator

Para / Finger	*r* mm	*e* mm	*t* mm	*u* mm	*l* mm	*L* mm	L_0 mm
Index finger	10	5	2	3	10	120	133
Middle finger	10	5	2	3	10	130	143
Ring finger	10	5	2	3	10	120	133
Little finger	9	4.5	1.8	3	9	99	112

Fabrication

The flexible pneumatic actuator is made up of two silicone rubber parts: a corrugated part and a bottom part. The two parts are fabricated by the way of casting molding, and their molds are shown in Fig.4. The molds are created using 3D printing. The two parts are bonded by using the same silicone rubber as the two parts.



(a) (b)

FIGURE 4. Molds. (a) Corrugated part of mold. (b) Bottom part of mold.

DESIGN AND TESTING OF FLEXIBLE HOOP-REINFORCED ACUATOR

Structure Improvement

It is clear that the radial expansion of the flexible actuator is severe when the air pressure in the actuator is bigger than 140 KPa. Besides, because the top layer and the bottom layer shared the same material, the actuator had a certain axial direction elongation. In order to solve this problem, it is assumed that axial restraint hoops (the yellow part in Fig.5) are added to the crest position of the actuator, and two non-stretchable strings (the purple part in Fig.5) are embedded in the bottom of the actuator. The improved actuator is shown in Fig.5, which is named as flexible hoop-reinforced actuator.

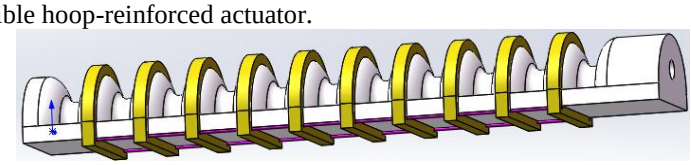


FIGURE 5. The structure of flexible hoop-reinforced actuator

Bending Angle Testing

In this study, the bending angle of the actuator is tested by using a flex sensor, FS-L-0112-103- ST, which should be calibrated before using. The experimental setup for bending angle testing of the actuator is illustrated in Fig. 6 (a). The actuator in actual testing is shown in Fig.6 (b). The front end of the flex sensor is fixed to the proximal cap of the actuator with rubber bands, and the other parts were covered with a square groove loop. The air pressure in the actuator gradually increases with the increments of 10KPa, and the angle is recorded by computer. The experiment is repeated four times to evaluate accuracy and repeatability. The test results for all finger actuators are shown in Fig.8 (a), (b) and (c). It can be seen that there is a certain degree of non-linearity between the bending angle and the input pressure.

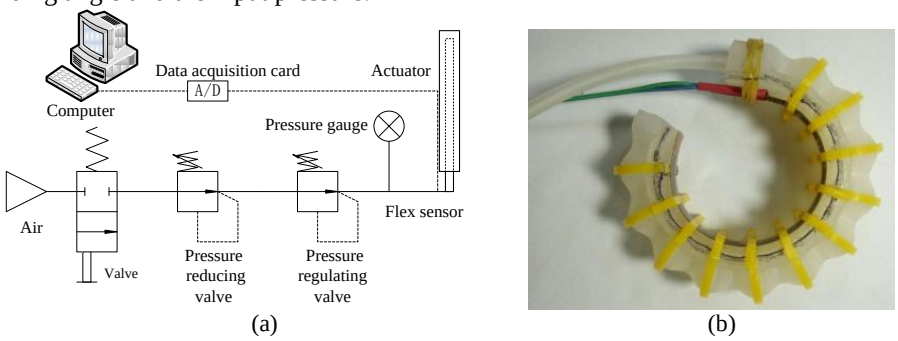


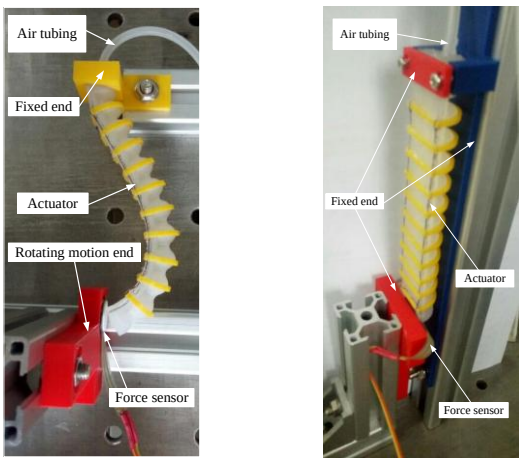
FIGURE 6. Bending angle testing. (a) Experimental setup for bending angle testing. (b) Photograph of actual testing.

Force Testing

To evaluate the force performance of the flexible hoop-reinforced actuators, two test schemes are proposed and a Force Sensing Resistor (FSR model 402) is used to measure the force. Scheme A is shown in Fig.7 (a), and Scheme B is shown in Fig.7 (b).

For Scheme A, the actuator is placed horizontally. Its end is limited to move in the same horizontal plane as the proximal cap, and the main part can freely deform in space. Since the tested force is perpendicular to the distal cap of the actuator, the rotating motion end needs to be adjusted to the position parallel to the distal cap during the test. The FSR is fixed on the rotary moving end and moves with it. Meanwhile, each time the position is adjusted, making sure that the center of the distal cap of the actuator is in the center of the FSR.

For Scheme B, the actuator is placed vertically. The bending deformation of the actuator is completely limited, and the force is only generated at its distal cap. The FSR is fixed on the fixed end of the fixture. For this scheme, the position of the actuator should be adjusted so that the center of the actuator distal cap is in the center of the FSR.



(a) Scheme A (b) Scheme B

FIGURE 7. Photograph of force testing

The test results of all actuators for the two schemes are shown in Fig.8 (d), (e) and (f). It can be seen that the force tested by the two schemes is quite different, and the force tested by scheme B is much larger than that of scheme A. Because Scheme B limits the bending deformation of the actuator, so that the contact force generated between the distal cap and FSR is very large. It can also be seen that the contact force generated between the

distal cap and FSR increases rapidly when the pressure applied in the actuator is larger than a certain value. Form the force result of scheme A, it can be seen that the influence of the crest radius r on the contact force is considerable: the smaller the r is, the smaller the contact force is. Meanwhile, *L* has certain influence to the output force. The smaller the *L* is, the harder the actuator produces bending deformation, so the larger the contact force is.

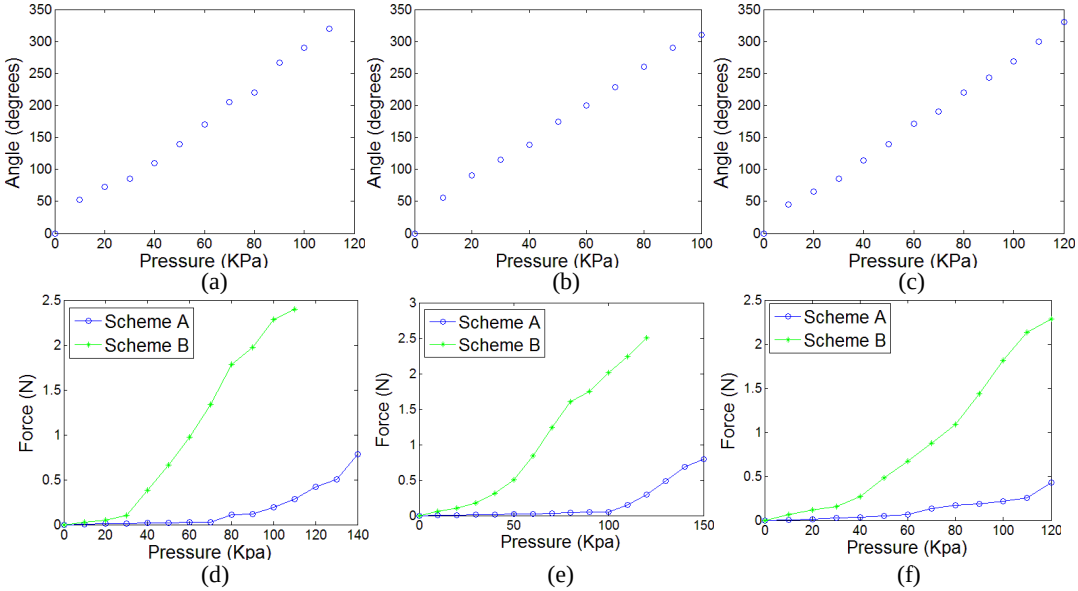


FIGURE 8. Testing results. (a) Bending angle of index finger& ring finger actuator. (b) Bending angle of middle finger actuator. (c) Bending angle of little finger actuator. (d) Force of index finger& ring finger actuator. (e) Force of middle finger actuator. (f) Force of little finger actuator.

Performance Comparison between Flexible Hoop- reinforced Actuator and Flexible Pneumatic Actuator without Hoop

The actuator with wave crest radius *r*=10mm, air chamber length *L*=110mm is chosen to make comparison with experimental value. The bending trajectory is recorded by a high speed camera. The force test is carried out with scheme A. Fig.9(a) and Fig.9(b) show the comparison of the bending performance and force properties for the two types of actuator. It can be seen from Fig.9(a) that the actuator with hoops can generate a greater bending deformation because the radial expansion is restricted by the hoop. It also can be seen from Fig.9(b) that the force properties of the actuator are greatly improved after adding the hoop. After adding the hoop, the radial deformation is effectively restricted, and the bending deformation of the actuator becomes larger under the same pressure, so the contact force increases. The performance of the flexible hoop- reinforced actuator is better than that of the flexible pneumatic actuator without hoop.

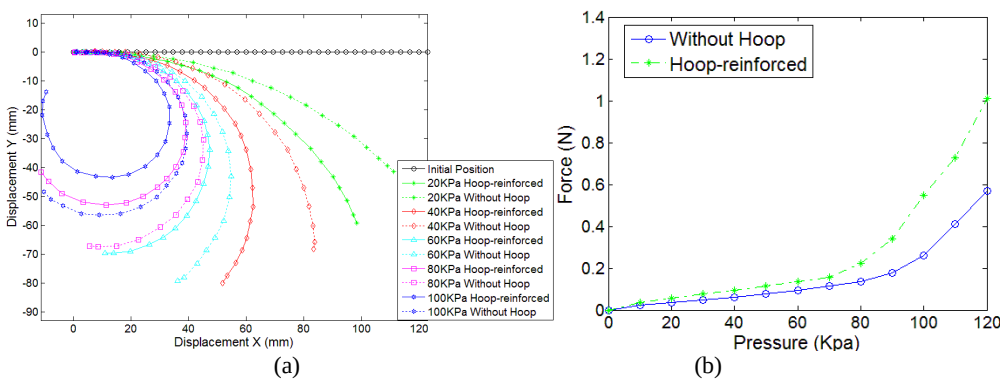


FIGURE 9. Performance comparison between flexible hoop-reinforced actuator and flexible pneumatic actuator without hoop. (a) Comparison of bending trajectory. (b) Comparison of force

DESIGN AND TESTING OF WEARABLE HAND REHABILITATION DEVICE

The wearable hand rehabilitation device is mainly made up of athletic gloves with a bit of elasticity and four finger actuators. The finger actuators' first and last hoops and the hoop near the second joint of the finger are sewed on the top surface of the athletic gloves, and a certain margin should be remained after sewing so that the fingers are able to bend normally. A piece of 2mm double-sided foam tape is put on the proximal cap of the actuator, and the two sides of the double-sided foam tape were bonded respectively on the distal cap of the actuator and the tip of the glove finger with adhesive. The proximal cap of actuator would produce a large downward concentrated force in the pressurized process of the actuator. If this force directly exerts on the back of hand, it would cause discomfort, so an arc-shape slice is bonded on the back of the glove, which is similar in shape to the back of the hand. The proximal cap of the actuator is fixed on the arc-shape slice using adhesive, so that the concentrated force exerted on the whole large arc-shape slice to reduce the discomfort of the back of the hand. The index singer actuator fixed on the top surface of the athletic gloves is shown in Fig.10(a).
The actual wearable hand rehabilitation device is shown in Fig.10(b). It is reliable to wear, convenient, and easy to take off, suitable for all kinds of people.

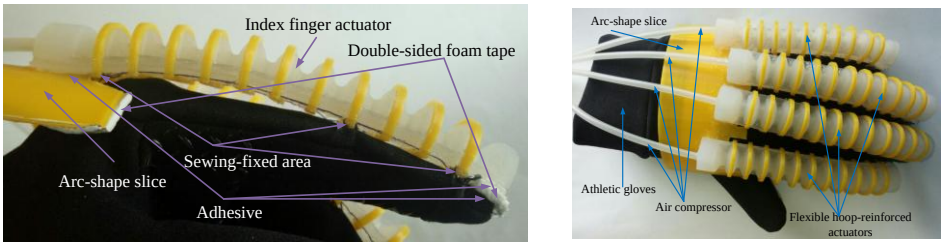
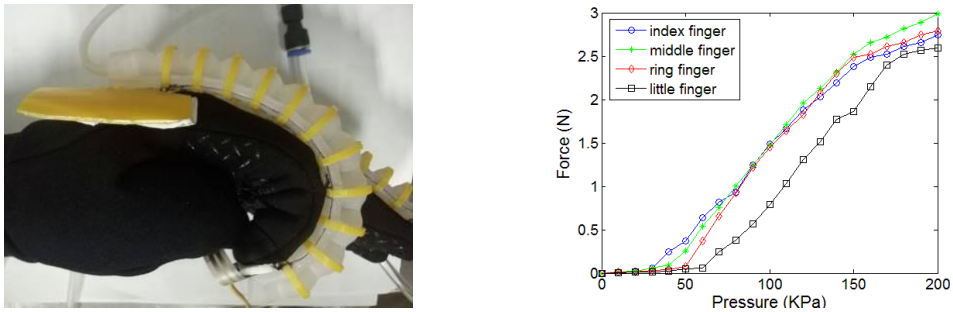


FIGURE 10. (a) Index finger actuator fixed on the top surface of the athletic gloves. (b)Wearable pneumatic rehabilitation device.

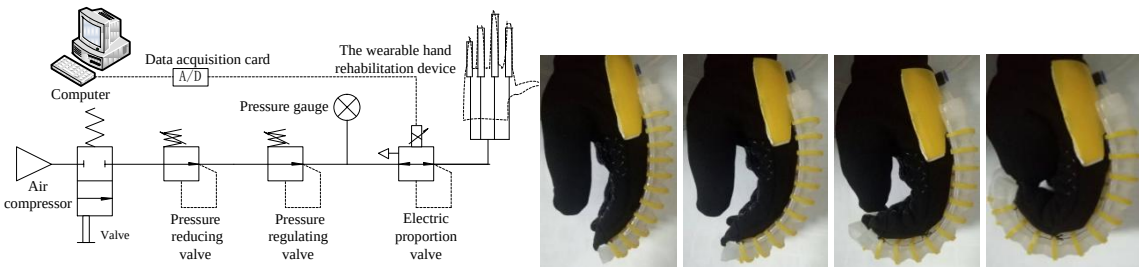
The test of the rehabilitation device is primarily to measure the force at the end of the actuator acting on the fingertip by placing the pressure sensor between the end of the actuator and the foam tape as shown in Fig.11(a). The output force results of the four finger actuators are shown in Fig.11(b). When the output force reaches 2.5N ~ 3N, the fingers will be completely bent. It can be seen that the hand rehabilitation device designed in this paper meets the requirements of finger rehabilitation training.



(a) (b)

FIGURE 11. (a) Testing of the rehabilitation device. (b) The output force of the rehabilitation device.

Pneumatic control circuit of the rehabilitation device for hand rehabilitation training is shown in Fig.12(a). The triangular function signal is input to the electric proportional valve by LabVIEW. The motions during hand rehabilitation training can be adjusted by adjusting the parameters of the signal.
By adjusting the input pressure, it can be found that when the input pressure is 200KPa, the finger is fully bent. So in the hand rehabilitation training process, set 200KPa as the maximum of input pressure. Fig.12(b) shows the motion of rehabilitation of rehabilitation gloves.
In the process of hand rehabilitation training, the flexible hoop-reinforced actuator' wave crest does not produce radial expansion due to the restraint of the hoop, and the wave valley part expands with the increase of the air pressure. but this does not affect the rehabilitation of the fingers. The whole rehabilitation training process is smooth. The flexibility is good and the output force of the actuator is appropriate, and there is no discomfort for fingers. The experiment proves that the rehabilitation device can help the patient to complete the rehabilitation training of the finger.



(a) (b1)70KPa (b2)100KPa (b3)160KPa (b4)200KPa

FIGURE 12. (a) Pneumatic control circuit. (b) Motions in different pressure

CONCLUSION AND FUTURE WORK

This paper presents the design, fabrication and testing of a wearable hand rehabilitation device fabricated using flexible hoop-reinforced actuators. Experimental results show the fingers will be completely bent when the actuators are pressurized at 200KPa, which can demonstrate that the developed hand rehabilitation device can meet the requirements of finger rehabilitation training.

The bending trajectory of the flexible hoop-reinforced actuator in free space is a standard circle when pressurized because each segment of the flexible hoop-reinforced actuator is the same. However, the trajectory of human finger isn't a standard circle when bending. In the future, we would improve the structure of the actuator, which make the structure of each segment different, to be close to the trajectory of human finger when the actuator pressurized.

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