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A Wearable Bionic Soft Exoskeleton Glove for Stroke Patients

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Abstract— **Hand dyskinesia in stroke patients greatly restricts their daily life ability. This paper presents a wearable bionic soft exoskeleton glove (Bio-exoskeleton Glove), which can help the stroke patients achieve two basic movement patterns: precision grip and power grip, and the patients wearing it can perform many activities of daily living. Based on human anatomy and biomechanics: the flexor digitorum profundus achieving the movement pattern of power grip, the flexor digitalis superficialis achieving the movement pattern of precision grip and the extensor digitorum achieving movement of finger extension are replaced by the tension line, a set of artificial exoskeleton muscles outside the hand is reconstructed. As the tension line is consistent with the muscles of hand in the fixed position and the direction of tension on the finger, the Bio-exoskeleton Glove has a strong human-machine coupling. Therefore, it can assist the stroke patients' hands to achieve the natural movement. This paper gives a detailed introduction to the principle and the structure design, and the Bio-exoskeleton Glove was tested for performance. The motion trajectory correlation between natural motion and the device-assisted motion reached 0.97 through experimental verification. The Bio-exoskeleton Glove can help the stroke patients basically achieve the motion trajectory of the human hand. Finally, through the patient test, the stroke patients wearing the Bio-exoskeleton Glove can achieve two basic movement patterns: precision grip and power grip.**

Keywords—bionics; exoskeleton; precision grip; power grip

I. INTRODUCTION

Stroke is a serious threat to human health and life[1]. It has the characteristics of high incidence, high mortality and high disability rate. About 80% of the survivors of the stroke have movement dysfunction (or paralysis) of hand and arm. However, the hand plays a very important role in human's daily life and is of great significance for human to maintain a healthy quality of life. Therefore, the rehabilitation of hand is particularly important[2, 3]. Rehabilitation of the hand needs a lot of repetitive work，so it requires a lot of labor. However, the application of exoskeleton robot technology[4] in rehabilitation therapy has greatly reduced the labor force[5].

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According to the structure properties of the exoskeleton robot, it is divided into two categories: rigid exoskeleton robot[6, 7] and soft exoskeleton robot[8]. Since the rigid exoskeleton robot has existed for many years, its defects are also increasingly apparent: 1) bulky and complicated structure, it's not convenient to apply it to daily activities; 2) high cost of treatment and longer treatment cycle, many ordinary families cannot afford it; 3) the rigid structure cannot be fitted perfectly with the hand, which easily cause secondary damage to the patients.

However, recently soft exoskeleton robots just make up for the shortcoming of rigid exoskeleton robot, and its compact, portable and soft features have attracted wide attention of researchers. For example, the intelligent rehabilitation machine hand (Gloreha) of Italy IDROGENET company is a set of finger rehabilitation systems for early rehabilitation of the stoke patients[9]. Kang et al. has designed a kind of tendon-driven wearable robotic hand based on polymer materials[10]. Park et al. developed a tendon-driven glove to help the stroke patients recover from the hand impairment[11]. Xiloyannis et al. provided a soft exosuit for assisting hand grasping in activities of daily living[12]. These soft exoskeleton gloves have the following disadvantages: 1) These soft exoskeleton gloves can achieve power grip operation, but the movement pattern of precision grip is less concerned. However, the movement pattern of precision grip is one of the most important movement patterns in daily life[13]. 2) the above structural designs have less analysis on the anatomical structure of the human hand, so the coupling of the exoskeleton Glove and the natural movement of human body is poor, thereby the comfort of the gloves is poor. 3) the design of the finger extension is unreasonable, causing two problems: too much pressure on the back of the finger and the hyperextension of the finger. Probably it can cause secondary damage to the patients.

In order to solve the above problems, a wearable bionic soft exoskeleton glove for stroke patients (Bio-exoskeleton Glove) is designed, which is based on the human anatomy principle and fully considers the stoke patients' comfort. Firstly, the finger anatomy model is established and analyzed. Secondly, the structure design of the Bio-exoskeleton Glove is made based on the muscle anatomical model. Thirdly, the kinematics test and motion test of the Bio-exoskeleton Glove in patients are carried out.

II. ANATOMIC ANALYSIS

There are two basic movement patterns which are termed precision grip and power grip, as shown in Fig.1(a, b). In precision grip the object is pinched between the flexor aspects of the fingers and that of the opposing thumb. In power grip the object is held as in a clamp between the flexed fingers and the palm, counter pressure being applied by the thumb lying more or less in the plane of the palm. These two movement patterns

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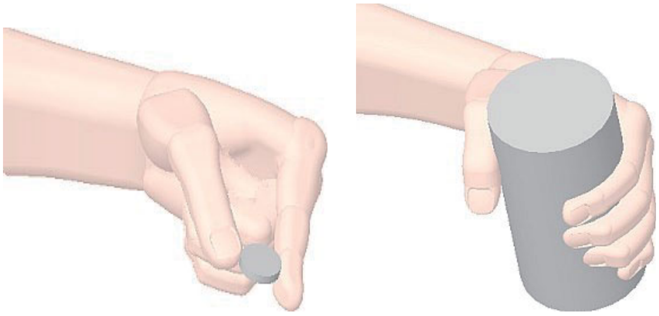
appear to cover the whole range of prehensile activity of the human hand[14]. In order to help the stroke patients with hand impairment accomplish these two movement patterns, and these two movement patterns are analyzed from the aspect of the anatomy of the finger.



(a) (b)

Figure 1. two basic movement patterns of the hand: (a) Schematic diagram of precision grip. (b) Schematic diagram of power grip.

The realization of these two movement patterns is related to two kinds of tendon: the flexor digitorum profundus tendon and the flexor digitorum superficials tendon. The tendon of the finger that can function successfully mainly depends on the three components: the stop point, the pulley and the muscle belly, as shown in Fig.2. The stop point is the attachment of muscles to the bones, which provides the force point. The stop point of the flexor digitorum profundus tendon is at the distal phalangeal bone. The stop point of the flexor digitorum superficials tendon is at the middle phalangeal bone. Pulley is a structure to limit the flexor tendon, providing a mechanical fulcrum for the flexor tendon and making its function fully functioning. The muscle belly is the source of the power for the whole movement, which drives the tendon through its contraction so as to drives the motion of the phalanx that is connected to the tendon.

Based on the anatomical principle of the human finger, the movement pattern of power grip is accomplished mainly by the flexor digitorum profundus tendon which drives the distal phalanx. The movement pattern of precision grip is accomplished mainly by the flexor digitorum superficials tendon which drives the middle phalanx.

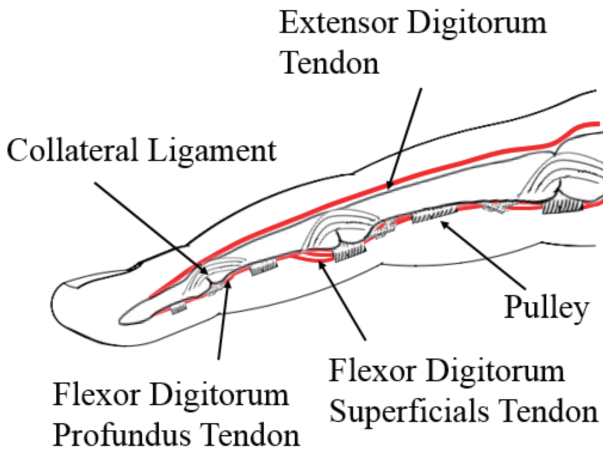
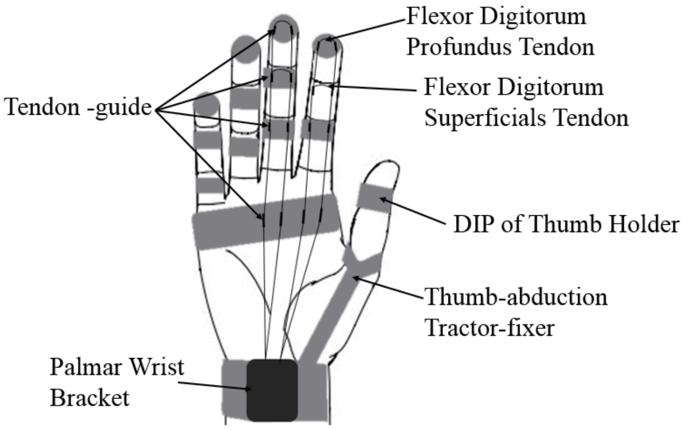


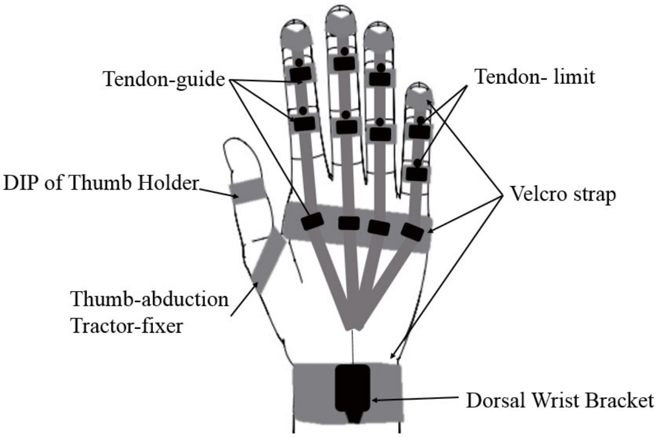
Figure 2. Anatomic structure of the finger

III. STRUCTURAL DESIGN

the Bio-exoskeleton Glove designed in this paper is composed of three parts, as shown in Fig.3. The first part: structure design of palm side. By imitating the flexor digitorum profundus tendon and the flexor digitorum superficialis tendon, the auxiliary hand can achieve two movement patterns of precision grip and power grip. The second part: structure design of palm Back. By imitating the extensor muscles of the hand, the hand wearing the Bio-exoskeleton Glove can complete the movement of extension. The third part: thumb structure design. In order to ensure the success of the grasping task, the thumb is fixed on the position where the space of purlicue is big enough. The main body of the Bio-exoskeleton Glove is the polyester glove, which has the characteristics of thin and good air permeability.



(a)



(b)

Figure 3. Schematic diagram of the Bio-exoskeleton Glove: (a) dorsal view. (b)palmar view.

A. Structure Design of Palm Side

In order to reduce the size and mass of the whole system, just like the three-finger manipulator, and the index finger and the middle finger of the Bio-exoskeleton Glove can be driven by the motor to achieve bending. Based on the anatomical analysis of the second part, the tendon is simplified as a tension line. As shown in Fig.4, the red tension line at the end to the distal phalanx imitates the flexor digitorum profundus tendon. Through the contraction of the red tension line, the movement pattern of power grip is realized. The green tension line at the end to the middle phalanx imitates the flexor digitorum superficials tendon, and the movement pattern of precision grip is achieved through the contraction of the green tension line. In order to limit the route of the tension line, the pulley of the hand in anatomy is replaced by the tendon-guide. The tendon-guide of the Bio-exoskeleton Glove is a hollow structure with a thickness of 2mm, which is made by 3D printing technology using high polymer material (PLA) with high hardness characteristics. In addition, the tendon-guide and polyester glove are connected together through Velcro strap, which can prevent a larger gap between the tendon-guide and the finger surface due to the force of the tension line in the process of using.

Figure 4. Palmar view of the Bio-exoskeleton Glove

B. Structure Design of Palm Back

Based on the anatomical analysis of the second part, the tension line on the dorsal part of the Bio-exoskeleton Glove is made by the 10mm strip cloth. The radial routing method is adopted to imitate the extensor tendons to achieve the extension of the remaining four fingers except the thumb. On the one hand, the increase in the width of the tension line reduces the pressure exerted on the back of the patients' fingers; on the other hand, the increase in the contact area between the tension line and the back of the fingers greatly reduces the probability of the finger extension failure.

In order to prevent the problem of hyperextension of fingers during the extension process, imitating the function of the lateral collateral ligament at the joints of the finger, the tendon-limit is designed and placed above each tendon-guide to restrict the joint' motion range, as shown in Fig.5. The tendon-limit is made by polymer materials (PLA), and it is sewn on the tension line of the back of the hand. In the process of finger extension, the extension range of each joint is determined by tendon-limit so as to ensure the using safety of the patient

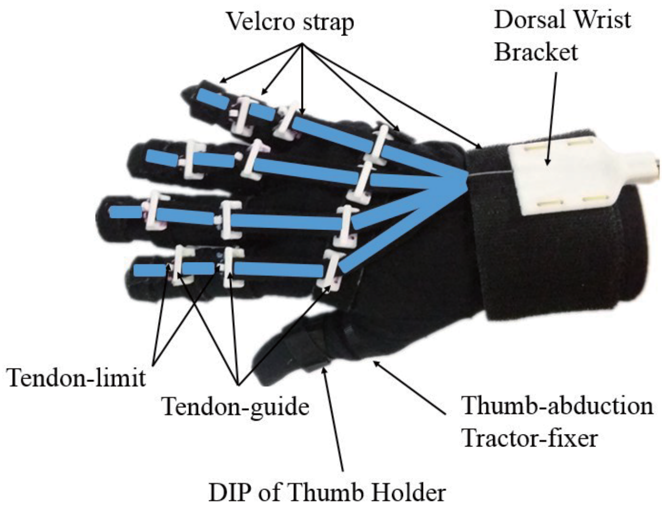


Figure 5. Dorsal view of the Bio-exoskeleton Glove

C. Thumb Structure Design

As we all know, the thumb plays an important role in the process of grasping the target object. And because of its high degree of freedom of the metacarpophalangeal joint (MIP joint), it is very complex to control it. However, we have found that the thumb is almost kept in a relatively fixed position in the process of grasping the target object. Therefore, the thumb is fixed in the position where the space of purlicue is big enough. The design of the thumb has two kinds of structures: the Thumb-abduction Tractor-fixer Velcro strap and the distal interphalangeal joint (DIP joint) of Thumb Holder Velcro strap. The DIP of Thumb Holder's main function is to keep DIP joint of the thumb straight. One end of the Thumb-abduction Tractor-fixer is fixedly attached to the root of the thumb and the other end is connected to the wrist strap, as shown in Fig.6.

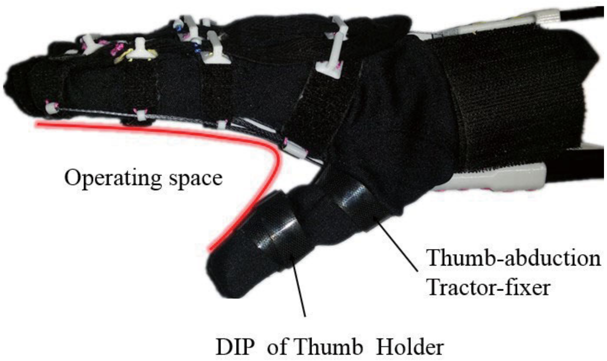


Figure 6. Radial view of the Bio-exoskeleton Glove

D. Actuation

In order to adapt to the grasping of irregularly shaped objects, the index finger and the middle finger are under the control of under-actuation, as shown in Fig.7. One end of the movable pulley is connected to the index finger and the other end is connected to the middle finger. The movable pulley is on the linear guide and driven by a direct current motor. Two direct current motors are needed since there are two movement patterns to be accomplished. The extension of the four fingers are driven by one direct current motor. The controller uses a single microprocessor chip, which realizes the drive motor by sending control commands to the direct current motor.

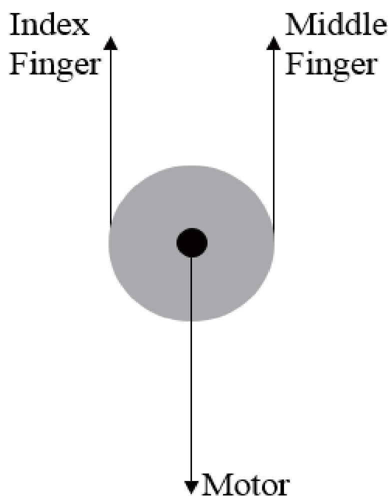


Figure 7. Schematic diagram of under-actuation

IV. Result and Discussion

In order to investigate the performance of the Bio-exoskeleton Glove, the kinematics test and the motion test of the Bio-exoskeleton Glove in patients were carried out respectively. The kinematic tests include the range test of the middle finger and the test of the motion trajectory. The kinematics test uses WISEGLOVE14 (WONSTAR Ltd, Beijing, China), a data glove used to measure the bending angles of every joint of the finger, as shown in Fig.8. It is used to measure the bending angles of the metacarpal joint (MCP joint) and the proximal interphalangeal joint (PIP joint) during the movement of the finger. Because the data of bending angle of the DIP joint of the finger cannot be obtained directly, it is necessary to deduce the approximate bending angle of the DIP joint according to the data of the PIP joint. Based on the physiological characteristics of the flexion of the finger, the bending angle of the DIP joint is the 2/3 of the bending angle of the PIP joint [15]. The bending angle data of each joint of the middle finger were collected at the 4Hz sampling frequency. Motion test of the Bio-exoskeleton Glove in patients was carried out under the supervision of a rehabilitative therapist.

Figure 8. WISEGLOVE14

A. Test and Analysis of the Range of Middle Finger Movement

The range test of the middle finger was carried out on a healthy subject wearing the Bio-exoskeleton Glove. The subject firstly wore the data glove (WISEGLOVE14) and then wore the Bio-exoskeleton Glove at the outside of the data glove, as shown in Fig.9. In order to prove that the subject does not control the movement of fingers autonomously in the process of test, we measure the EMG signals of the flexor and extensor muscles of the forearm to determine whether the subject has autonomic movement. The values of EMG signals prove that the subject exerts no force.

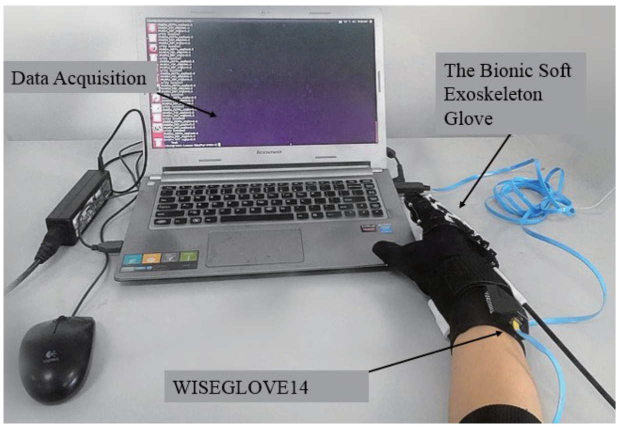


Figure 9. Test set-up for kinematics test

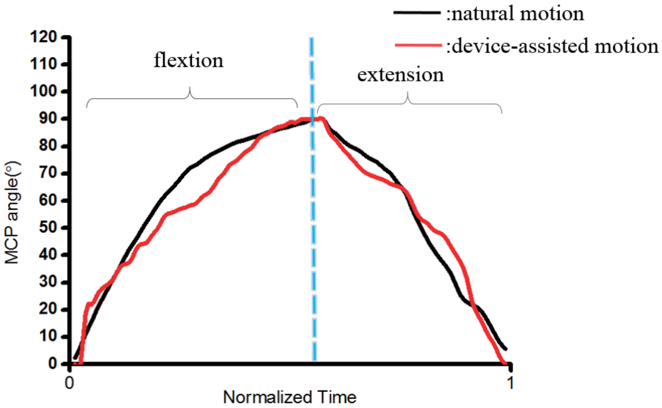
As seen in Table1, the bending and extension range of each joint with the Bio-exoskeleton Glove is almost the same as that of the natural finger movement. Although the maximum bending angles of PIP joint and DIP joint are 10 degrees smaller than that of the natural movement of the middle finger respectively, it is sufficient to help the stroke patients with hand impairment achieve the two movement patterns in their daily life.

TABLE I. RANGE COMPARISON OF MIDDLE FINGER MOVEMENT

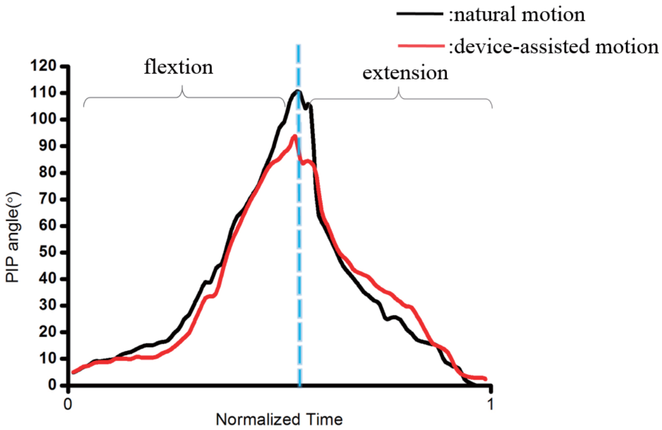
Joint	Motion	Range of Motion (°)	Range of Motion with the Bio-exoskeleton Glove (°)
DIP	Flexion	73	62
	Extension	0	3
PIP	Flexion	110	93.7
	Extension	0	2.4
MCP	Flexion	90	90
	Extension	0	2.4

B. Motion trajectory analysis

In order to further prove that the Bio-exoskeleton Glove do not cause a secondary damage to the fingers, the comparison test of motion trajectory is also carried out by a health subject using the test set-up of kinemics test. Because the natural motion speed of the fingers and the device-assisted motion speed of the fingers is not the same. The natural motion speed is standardized according to the speed of the Bio-exoskeleton Glove. Finally, the natural motion angle trajectory of each joint is compared with that of each joint assisted by the Bio-exoskeleton Glove. The experimental results are shown in Fig.10.



(a)



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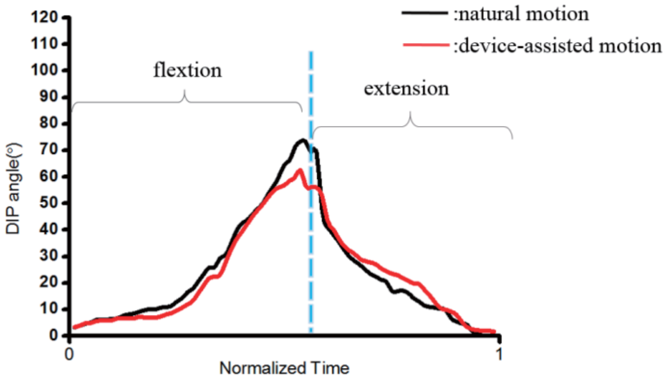

(c)

Figure 10. Motion trajectory comparison: (a)MCPjoint. (b)PIPjoint. (c)DIP joint.

As shown in Fig.8, the whole movement in the experiment consists of two processes: the flextion of the middle finger and the extension of the middle finger. The blue vertical line in the figure indicates the dividing line between the flextion process and the extension process. It can be seen from the figure that the bending speed is slightly faster than the extension speed. In the flextion process, the sequence of the joint movement is MCP joint, PIP joint and DIP joint. In the extension process, the sequence of the joint movement is MCP joint, PIP and DIP joint. The joint angles when the middle finger is fully extended did not appear negative angles, therefore the Bio-exoskeleton Glove solved the hyperextension problem.

In order to analyze two motion trajectory relevance theoretically, MATLAB's correlation function of Pearson Correlation Coefficient is used to analyze the data correlation of MCP, PIP, and DIP in the two sets of data. The results are as follows: the correlation coefficient of MCP is 0.973, the correlation coefficient of PIP is 0.977, and the correlation coefficient of DIP is 0.977. From the experimental results, it can be concluded that the device-assisted motion trajectory of the fingers is highly similar to natural motion trajectory of the fingers, which is conducive to the rehabilitation of the stroke patients.

C. Motion test of the Bio-exoskeleton Glove in patients

In order to demonstrate the actual effect of the Bio-exoskeleton Glove based on anatomy in the rehabilitation of patients, motion test of the Bio-exoskeleton Glove was carried out on the two patients respectively: a stroke patient and a paraplegia patient, as shown in Fig.11. The stroke patients have no mobility in the hand and arm, and the paraplegia patient’s arm has the mobility but his hand has no mobility.

(a)

(b)

Figure 11. Motion test of the Bio-exoskeleton Glove in patients. (a) the stroke patient. (b) the paraplegia patient.

As you can see in the figures, the Bio-exoskeleton Glove can help stroke patient and paraplegia patient accomplish the movement of the grasping. It can be seen from the patient's use effect diagram that under the assistance of the Bio-exoskeleton Glove, the hand of patients can be completely opened and closed, and patients can achieve the movement of precision grip smoothly. In addition, the feedback of use from the patients is good, and the patients have no discomfort during the process of using. The results of motion test of the Bio-exoskeleton Glove in patients directly prove that the movement of the Bio-exoskeleton Glove conforms to the voluntary movement of the hand and is beneficial to the rehabilitation of the hand.

V. Conclusion

This paper presents a wearable bionic soft exoskeleton glove for stroke patients based on the biomechanics principle, which can achieve the natural movement patterns： precision grip and power grip and enhance the activities of daily living of patients. the Bio-exoskeleton Glove designed in this paper is mainly made of polyester and polymer material (PLA), so it is light in weight and will not bring heavy load to arm movement of the patients. Since polyester glove is connected with other structure of the Bio-exoskeleton Glove through Velcro strap, the patients can make fine-tune to accommodate the size of the patients' hand. The Pearson Correlation Coefficient of the motion trajectory between the device-assisted motion and the natural motion can reach 0.977, which shows that the Bio-exoskeleton Glove has the high bionic motion performance. Motion test of the Bio-exoskeleton Glove in patients also proves that the u of the Bio-exoskeleton Glove is conducive to the rehabilitation of the stroke patients' hands.

In the future, a compact, lightweight, ergonomic exoskeleton glove will be made, and the driving mechanism and control unit will be integrated into a backpack, which can make patients comfortable for a long time using.

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