

Design and Kinematic Simulation of a Novel Exoskeleton Rehabilitation Hand Robot

Shuxiang Guo^{1,2,3}, Weijie Zhang^{1,2}

¹Tianjin Key Laboratory of the Design and Intelligent Control of the Advanced Mechatronical System, Tianjin, 300384, China
^{*corresponding author:} jianguo@tjut.edu.cn

Jian Guo^{2*}, Jiange Gao^{1,2}

²Tianjin Key Laboratory for Control Theory & Applications in Complicated Systems and Biomedical Robot Laboratory Tianjin University of Technology Binshui Xidao 391, Tianjin, China
zwhj316@163.com

Yuye Hu²

³Intelligent Mechanical Systems Engineering Department Kagawa University 2217-20, Hayashi-cho, Takamatsu 761-0396, Japan
guo@eng.kagawa-u.ac.jp

Abstract –The rehabilitation exoskeleton robot is more and more used in the assisting stroke patients in implementing rehabilitation training. In this paper, a novel exoskeleton hand robot which was driven by cable has been proposed to aim at helping varieties of paralyses patients recover motor function. This exoskeleton hand rehabilitation robot system mainly consists of exoskeleton hand robot, EEG system, motor controllers unit, some sensors and a workstation. And the hand exoskeleton mechanism was portable, wearable and adjustable for patients doing home rehabilitation training. Based on the parameters from human hand, the kinematic model of hand robot was established to be used in designing and the kinematic simulation experiments about this exoskeleton hand robot were done. Through the simulation software ADAMS (Automatic Dynamic Analysis of Mechanical Systems), the parameters of position, angle velocity and angle accelerated velocity (PVA) of proximate inter-phalanger (DIP) distal inter-phalanger joint were simulated. And then, the movement situation of the DIP joint was obtained according to the data from the position encoder. So the velocity curve and accelerated velocity curve were obtained by calculating the actual position function derivation. The simulated results showed that this exoskeleton hand robot has high movement ability to finish the continuous passive motion (CPM). Beside that, a comparison test was done to verify whether there were some motion blocks in wearing exoskeleton robot. Through analyzing the experimental data, the error between the actual position and the simulated position of the PIP joint of the finger was very small which verified the small interference of robot. These experiments demonstrated that the exoskeleton hand robot has high efficiency movement ability for stroke patients who need to do the finger rehabilitation training. In the future, the optimization design of the exoskeleton hand robot will be done in order to improve more movement ability.

Index Terms- Hand exoskeleton rehabilitation robot; Cable-driven; Kinematic simulation; Rehabilitation robot system;

I. INTRODUCTION

Stroke which is caused by acute cerebra-vascular disease has become a major threat to human health. Those patients with this disease is mainly caused by the loss of the limb motor function and related complications, especially the loss of upper limb movement function. Most of the patients with stroke cannot take care themselves, which not only lead to

patients' physical and psychological pressure increasing rapidly, and brought heavy burden to the families and society. The modern medicine for the treatment mainly adopt acupuncture, massage, and the method of electrical stimulation. The rehabilitation methods is mainly physical therapy for patients with one-on-one treatment. Not only the resources consumption for the human and material is very large, and there is no a scientific evaluation method for rehabilitation. Besides, the enthusiasm of the rehabilitation training for patients are greatly reducing, due to the process of treatment is very boring. Therefore, some researchers proposed the theory of continuous passive motion (CPM) [1] [2]. continuous passive motion of the sick body stimulate the patient's body, the stimulation from the sick body which is continuous passive exercising will promote the recovery of the motor nerve in brain, and then the patients will obtain the ability of movement. In this situation, many researchers applied the robot technology to the field of rehabilitation. It not only can provide effective rehabilitation training, and the burden of clinical medical staff and patients will be reduced. In addition, through some sensor technology, the recovery situation can be recorded in any time, when the rehabilitation robot is working[3]-[5]. According to the relevant data from the sensors on the robot, the doctor can provide objective and accurate treatment methods and evaluating parameters. At present, the electrical technology also gradually be applied to the field of rehabilitation[6]-[8].

As we know, hand is one of the most indispensable parts in human body. However, because of the specialty of finger bone features, it is easy to loss motor function for the patients with stroke. Many nerve blood vessels and many small muscles are all over in whole hand, so the treatment for hand injury is very difficult, and the time of rehabilitation after treatment is longer relatively. Usually, movement function of upper limb in patients with stroke mainly start from the shoulder, and end at fingers. Therefore, finger movement function recovery will be a standard of upper limb rehabilitation situations in the medical field. Over the past twenty years, with the rapid development of the exoskeleton rehabilitation robot, many well-known research institutions in domestic and foreign have also begun to develop a variety of

exoskeleton hand robot.

Since the last century seventy's, robot techniques are applied in the field of rehabilitation, and they successfully replace the traditional physical therapist and can provide high reliability and high strength training for patients to recover motor function. At the same time, more and more rehabilitation robots are applied on the treatment of the patients with stroke. In 2010, American scientists Sasha Blue Geoffrey studied an exoskeleton hand rehabilitation robot system named HEXORR, it can assist patients move their cramps fingers. The system can provide free motion and the constrained motion of two kinds of pattern, and it can improve the possibility of the recovery and training effect through an interactive virtual reality games [9]. Kagawa University in Japan developed the exoskeleton hand robot. Joint angle sensors with potentiometer which had force feedback function are mainly adopted[10]. Song Z designed an upper limb exoskeleton rehabilitation robot which was driven by a wire line. It could complete the bend and stretch motion of elbow. This device was very suitable for severe patients with paraplegia because simple structure and light quality were the characters of this robot[11]. A multi-degree of freedom hand exoskeleton robot was designed by American scientist Talha Shahid in 2013, it has an advantage of low cost [12]. Marco designed a wearable hand rehabilitation robot with self-Aligning joint Axes which is used to the rehabilitation training of patients [13].

The exoskeleton hand rehabilitation robot research in China started relatively late. But in recent years, due to the rapid development of robot technology, many universities and research institutions began to research exoskeleton robot.

In 2011, the Hong Kong Polytechnic University K.Y.Tong, developed a novel exoskeleton hand robot system for stroke patients' rehabilitation. This robot had 5 fingers with two degrees of freedom each finger. This robot is mainly controlled and evaluated by the electrocardiograph signal, and a built-in embedded electrocardiograph signal controller was applied in this robot[14]. In 2012, an exoskeleton hand rehabilitation equipment developed by Beijing University of Aeronautics and Astronautics. Exoskeleton joint units based on the structure of parallel sliding block which is drive by the micro wire were adopted. It can stimulate rehabilitation therapy according to signals feedback from joint position sensors and the strain of the force sensor [15]. Tianjin University of Technology developed a hand CPM rehabilitation equipment in 2014, adopting the exoskeleton joints based on four bar linkage unit. Patients can adjust the robot's motion parameters according to the data displayed on the touch screen [16].

So far, the exoskeleton rehabilitation hand robot had made some achievements after years of research and development, and robots which were researched by some institutions were mainly using in clinics and hospitals. But there are some problems existed. First of all, most of the rehabilitation robots are not suitable for rehabilitation training at home because of their huge body. Secondly, some designed hand robots were so complex and heavy that , and the installation process was so

complicated. Then, most of the robots mainly adopted the method of separate actuators and driving mechanism. In the end, rehabilitation training system is not collected biological electrical signals of the brain, there was not a comprehensive scientific evaluation system about the patients' recovery. Therefore, it is necessary to design a portable exoskeleton hand rehabilitation robot system with auxiliary patients in rehabilitation training at home.

In this study, a novel hand exoskeleton rehabilitation device has been proposed and designed. The rest parts of this paper are organized as follows. In section II, the design of the robot structure and the rehabilitation processing are introduced. Then according to the human finger stone characteristic, the kinematic model of the finger is built in SolidWorks software. By the experiment, some kinematic parameters of the hand robot are simulated in section III. The final part is the conclusions and future work for the whole paper.

II. DESIGN OF THE ROBOT STRUCTURE

A. Structure and Motion Model of Hand

In this paper, a novel exoskeleton hand rehabilitation robot system based on EEG signals is proposed, it can improve the enthusiasm of the patients with training and is suitable for family use. As shown in figure 1, the system consist of exoskeleton rehabilitation hand robot, brain electrical signal system, electrocardiograph signal system (EMG), the human-computer interaction system, motor control unit, relevant sensors and workstation. In addition, by adopting the light materials, this hand robot is lighter weight than the exoskeleton rehabilitation hand robots before. The designed parts of mechanical structure design and the kinematic simulation about the hand robot are introduced in this paper.

In the process of rehabilitation training, the exoskeleton hand robot move through the links fixed on the fingers of the patients with paraplegia. When the patients get some stimulation from human-computer interaction system, their brains will produce EEG signals. By analyzing these signals from brain electrical signal collector and the results are put out to the workstation, and then the motor control unit can drive exoskeleton rehabilitation hand robot to do some exercise according to the results from signal collector.

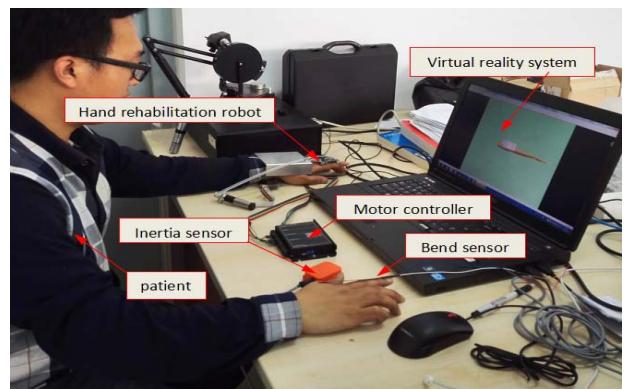


Fig.1 The structure of the exoskeleton hand robot system

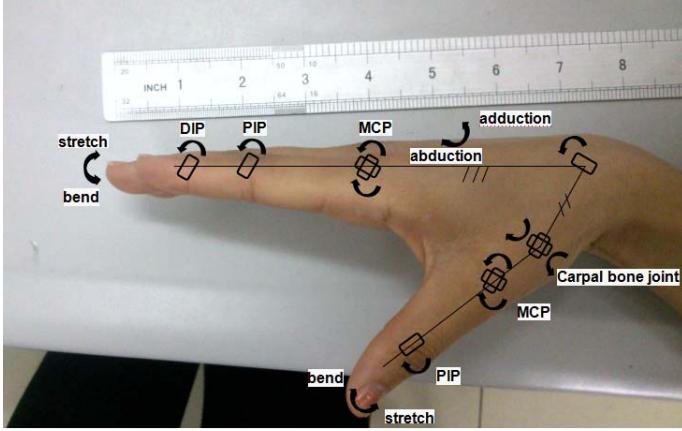


Fig.2 The structure and motion characteristic of the human hand.

At the same time, the bend sensor fixed on the robot can record the bending angle of the hand robot and ensure security of the training. Doctors can get some robot's movement information from the MTx inertial sensors, including the displacement, velocity and acceleration velocity, and then we make better rehabilitation strategy for patients according to these information. Electrocardiograph signal system can help doctors to observe the situation of patients in real time.

B. Human Hand Structure Analysis

Because the robots are used to assist the training of the human body, so taking full consideration to the ergonomic requirements is necessary in the process of designing. Therefore, we need to analyze the structure of human body hand before design the hand robot.

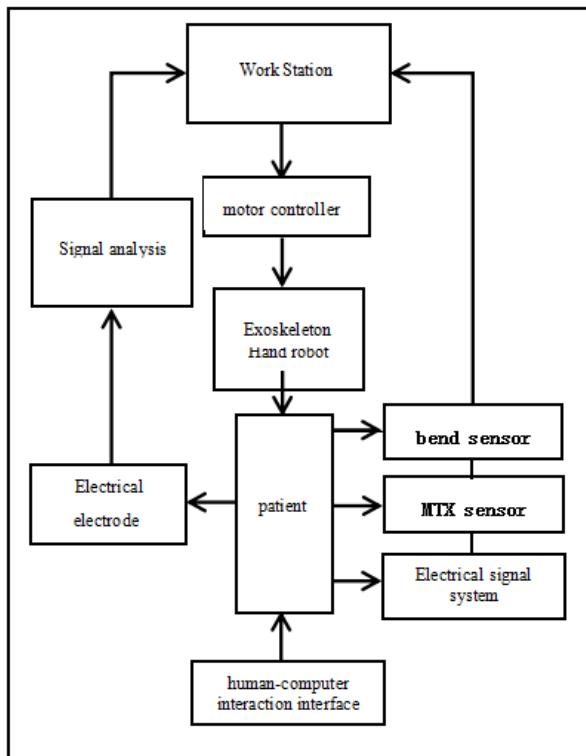


Fig.3 The flow chart of rehabilitation training

Tab.1 The motion range of the finger joints

joint	MCP joint	PIP joint	DIP joint	CMC joint
Bend/Stretch (/°)	0~90	0~110	0~90	-15~30
Adduction/abduction (/°)	-15~15	---	---	-10~15

The hand of the human mainly include bones, muscles, skins and soft tissues. As shown in figure 2, 21 degrees of freedom are needed to complete the daily life. Among them, there are five degrees of freedom in your thumb and one degree of freedom in your knuckle joint, one degree of freedom in joint, and three degrees of freedom in the wrist joint. In addition to the thumb, the other four fingers have the same structure, joint have two degrees of freedom, there is a degree of freedom and the proximate inter-phalanger (DIP) distal inter-phalanger joint with one degree of freedom.

There are mainly two kinds of constraints in your fingers, the first one is a physiological structure of the constraints, refers to the movement scope each finger joints can achieve, which is shown in table 1.

Another constraint is coupling effect between joints, such as middle finger joint can produce a small amount of bend when we bend joint of the index finger. In addition, there is a bending constraint relations between the proximate joints and distal joints as follows:

$$\theta_{distal} = 0.46 \times \theta_{prox} + 0.083 \times \theta_{prox}^2 \quad (1)$$

C. Structure Design of Rehabilitation Exoskeleton Hand Robot

In 2013, we developed a exoskeleton hand rehabilitation robot in which the belt driven institutions is adopted by using D-H parameters method. According to ergonomic characteristics, the exoskeleton hand robot is designed in Fig. 4. Some adjustable length devices were designed to meet the needs of different patients. The hand robot has 3 DOFs in total, including MCP, PIP and DIP joint, to assist patient implement the flexion and extension movement of each finger except the thumb. This hand robot adopts the motor drive method, which is fixed on the palm part. And the transmission way selects the micro synchronous tooth belt cooperation, because it has many advantages for easy installation, high transmission efficiency and light weight. Because of the driving mechanism adopted toothed belt transmission mechanism, the space take up by the motor is larger relatively. So the robot can only achieve a single finger rehabilitation training. The thumb mechanism will not be added to achieve the whole hand motion, if the driving mechanism is not changed.

In view of the above shortcomings of exoskeleton hand rehabilitation robots, we put forward a more optimized exoskeleton hand rehabilitation robot. This robot is mainly adopts light materials such as nylon, aluminum alloy and copper. The total weight of the robot is only 52 g, which can be worn on the patient's fingers directly. There are a total of three degrees of freedom, can help patients to complete

bending and stretching motion of the finger joint, proximate inter-phalanger joints and the distal inter-phalanger (DIP).

On the drive way, three driving mode (pneumatic mode, hydraulic and electric way) are mainly applied on the exoskeleton robot. Compared with the other two ways, electric driving has many advantages such as simple structure, light weight and easy control, etc. In addition, the electric driving way has a high level of integration compared with the other two methods. It not only can combine the driving mechanism and transmission mechanism, but also helps to save the room of the system. The driven motor is installed on the back of hand, so that we can use hand to undertake motor. The virtual model of the robot which is designed through Solid-works design software is shown as the fig.5. This robot mainly adopts under-actuated driving mode, namely one motor can achieve more degrees of freedom. In the drive mode, the hand rehabilitation robot mainly adopts string transmission mode with remote driving structure, convenient installation, compared with the existing gear transmission.

When the string wheel which is driven by the motor drives cable to move forward and back, the link mechanical structure which is drive by the string enable the fingers of patient do some exercise as the designed motion.

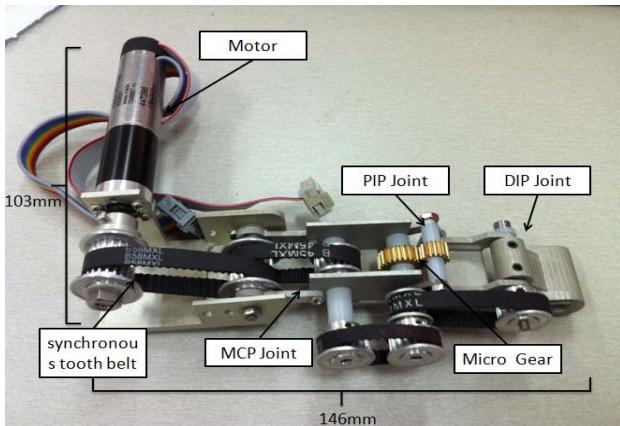


Fig.4 The previous prototype of the rehabilitation exoskeleton hand robot

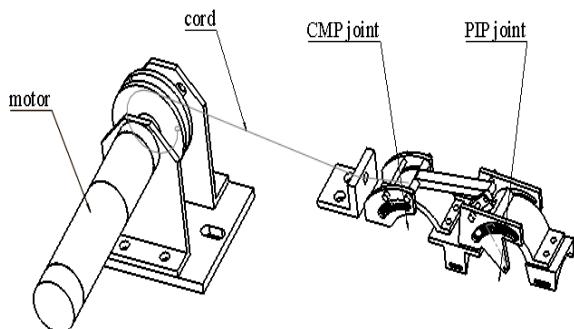


Fig.5 The design drawing of the rehabilitation exoskeleton hand robot

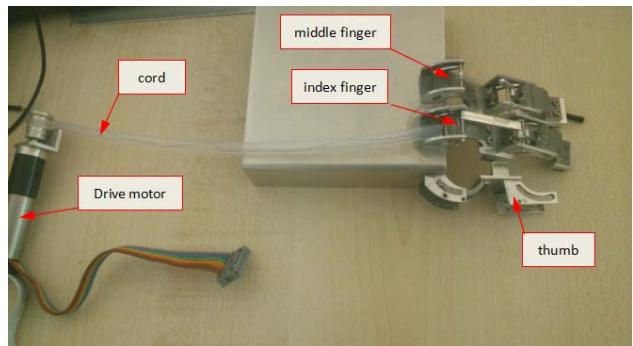


Fig.6 The prototype of the rehabilitation exoskeleton hand robot

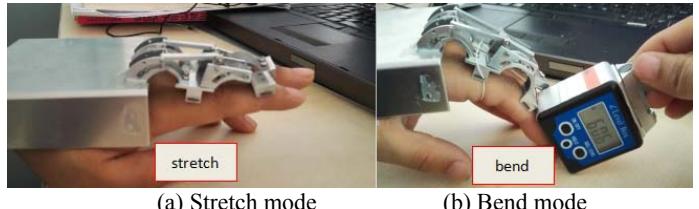


Fig.7 The extension and flexion motion of the exoskeleton rehabilitation hand robot

At the same time, the film bend sensor is attached on the robot in the bottom, used to detect the bending angle of rehabilitation training. According to the design requirements, the exoskeleton hand rehabilitation robot prototype described as shown in figure 6. It can be worn on the patients' fingers directly. The bending and stretching situation of single finger are shown in fig.7.

III. KINEMATIC SIMULATION OF THE ROBOT

A. The Kinematic Simulation of The Exoskeleton Hand Robot

The motion simulation software mainly used in robot field is mainly ADAMS (Automatic Dynamic Analysis of Mechanical Systems). It has the characteristics of simple and easy to operate in the aspects of the kinematics and dynamics simulation of the robot, but the progress that established 3D models using ADAMS software is relatively complicated and not easy to be operated. Therefore, we established the virtual models of exoskeleton hand rehabilitation robot through SolidWorks design software. When the 3D model of robot was done, the 3D models must to be inverted to Para-solid type file which is imported into ADAMS through the two software seamless interface. In the ADAMS simulation environment, the useless part models such as bearings, screws and nuts must to be delete to accelerate simulation running time. The rotating vices were applied in rotary joints such as MCP joint and PIP joint. The simulated model of hand rehabilitation robot is shown in figure 8.

Besides, the Boolean operation was used to merge several adjacent parts which have little movement relatively into one part.

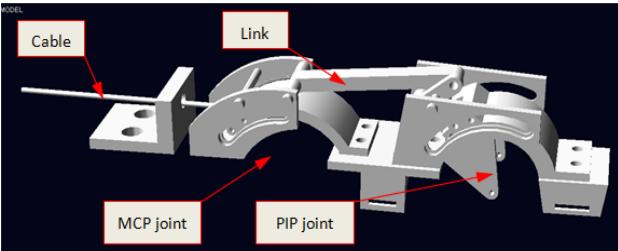


Fig.8 The virtual model of the exoskeleton hand rehabilitation robot

In the simulation setup, virtual machine running process was divided into forward and back process. In order to make the shock phenomenon not be appeared, the motor running process was divided into accelerated phase, smooth running and slow down phase. The drive speed function is following as:

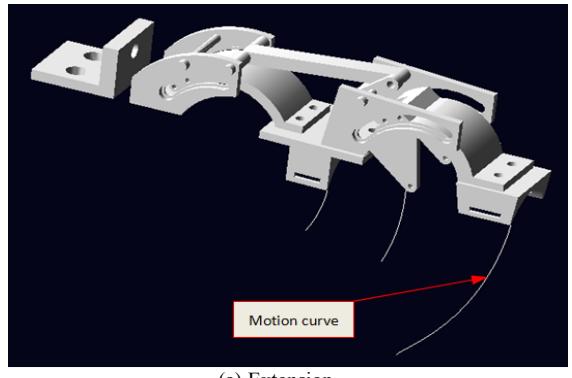
$$F(\text{time}) = \text{STEP}(\text{time}, 0, 0, 2, -1.0d) + \text{STEP}(\text{time}, 2, 0, 8, 0) + \text{STEP}(\text{time}, 8, 0, 10, 1.0d) + \text{STEP}(\text{time}, 10, 0, 12, -1.0d) + \text{STEP}(\text{time}, 12, 0, 18, 0) + \text{STEP}(\text{time}, 18, 0, 20, 1.0d)$$

B. Experiment Results

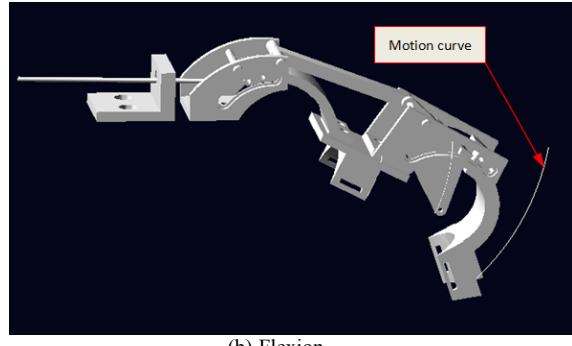
From the result, we can see that the robot will achieve 8.5 s movement back and forth, white line in the trajectory is shown in figure 8. We can see from the figure, the robot can achieve bending and stretching, and there is no dead point problem, conform to the requirements of the human hand movement and exercise.

The results of the hand movement situation are exported with post-processing function of ADMAS software, as shown in figure 10, which includes the angle position, velocity and acceleration velocity of the PIP joint of the finger robot. Besides that, the actual data of the PIP joint of the finger are shown in the fig.10. From this figure(a),the error between the actual position and the simulated position of the PIP joint of the finger is very small, it is only 3%,and the maximal displacement of the terminal point on the x y plane direction (the z axis fixed) is 64 mm in motion mode. The change situation of the PIP joint of the finger in actual angle velocity and the simulated angle velocity are shown in the figure (b), when the time is 20.0s, the max error between actual angle velocity and the simulated angle velocity is 2rad/s when the time is 1.8s, the max bending angle of PIP joint is 9.2 rad/s; when time is 18s, the maximum speed of stretching is -9.2 rad/s. The actual accelerate speed and the simulated accelerate speed of the PIP joint is shown in the figure(c), when time is 0.4s, the max error between the actual accelerate speed and the simulated accelerate speed of the PIP joint is12 rad/s².The max actual accelerate speed is 23 rad/s² when time is 0.4s.But the actual accelerate speed of the PIP joint is relatively stable from 2.3s to 7.5 s and from 13s to 16.5s, there is a rapidly rising trend before 2.3 s.

The exoskeleton hand robot can move smoothly and there are not obvious oscillation when the robot change its move direction. So this robot can be used to assist rehabilitation training of paraplegia patients.



(a) Extension



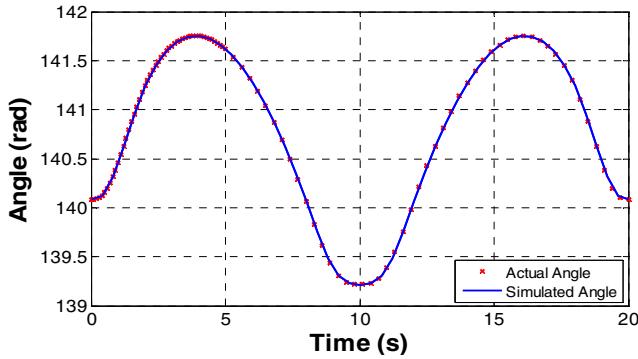
(b) Flexion

Fig.9 The motion trajectory of the exoskeleton hand rehabilitation robot

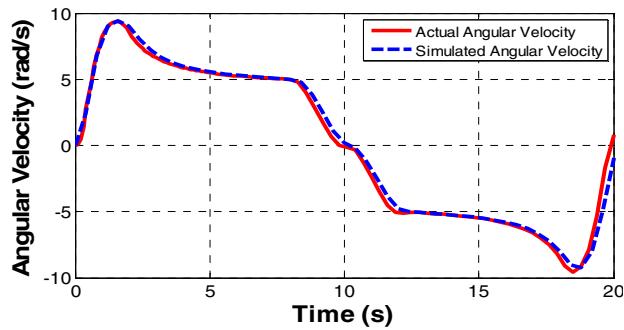
IV CONCLUSIONS AND FUTURE WORK

In this paper, a novel exoskeleton hand rehabilitation robot was proposed to assist the stroke patients to recovery the motion function of hand. The cable-driven way which could realize the long distance transmission was adopted in this hand rehabilitation robot system. Besides, it could realize the family rehabilitation training in any time because this robot could be worn on the fingers of the patients very well. The main structure and the kinematic simulation of the exoskeleton hand rehabilitation robot which adopted the under-actuated driven way was proposed in this paper. ADMAS simulation software was used to analyze the movement of the exoskeleton hand rehabilitation robot. From the results of the simulation, robot has some advantages of smooth movement, no dead point and small vibration. Besides that, this hand rehabilitation robot mainly adopted the human body engineering and it can be worn in the human fingers very well. And this exoskeleton hand rehabilitation robot can satisfy the demands of the human finger movement, suitable for wearing in the hands of patients with stroke.

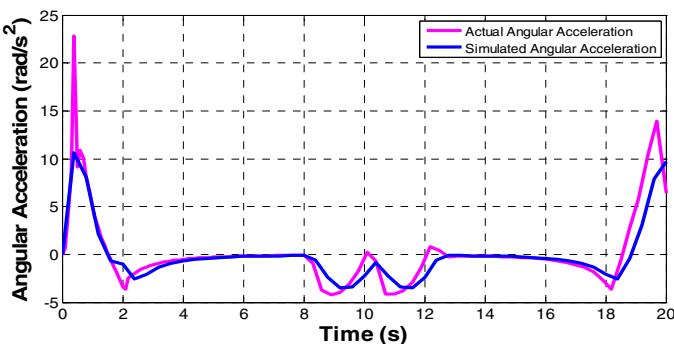
In the future, the dynamic model of the robot will be considered to add the control method. Besides, we will consider the movement force in each joint for decreasing the secondary damage of patients in the training.



(a) The angle curve for the simulation and the actual movement of the PIP joint



(b) The angle velocity curve for the simulation and the actual movement of the PIP joint.



(c) The angular acceleration curve for the simulation and the actual movement of the PIP joint.

Fig.10 The motion situation of the hand robot end-effect

ACKNOWLEDGMENT

This research is partly supported by National High Technology Research Development Plan (863 Plan: 2015AA040102) and Key Project of Scientific and Technological Support of Tianjin (15ZCZDSY00910).

REFERENCES

- [1] Songyuan Zhang, Shuxiang Guo, Muye Pang and Mohan Qu, "Training Model-based Master-slave Rehabilitation Training Strategy using the Phantom Premium and an Exoskeleton Device," Proceedings of the 2014 ICME International Conference on Complex Medical Engineering, pp. 105-110, Taipei, June 26-29, 2014.
- [2] Songyuan Zhang, Shuxiang Guo, Mohan Qu, Muye Pang, "Development of a Bilateral Rehabilitation Training System Using the Haptic Device and Inertia Sensors," Proceedings of 2014 IEEE International Conference on Mechatronics and Automation, pp.1237-1242, August 3-6, Tianjin, China, 2014.
- [3] Songyuan Zhang, Shuxiang Guo, Baofeng Gao, Hideyuki Hirata, Hidenori Ishihara, "Design of a Novel Telerehabilitation System with a Force-Sensing Mechanism," Sensors, vol.15, pp.11511-11527, 2015.
- [4] Shuxiang Guo, Xin Zhao, Wei Wei, Jian Guo, Fang Zhao and Yuye Hu, "Feasibility Study of a Novel Rehabilitation Training System for Upper Limb Based on Emotional Control," Proceedings of 2015 IEEE International Conference on Mechatronics and Automation, pp.1507-1512, August 2-5, Beijing, China, 2015.
- [5] Christopher J. Nycz, Tobias Bützter, Olivier Lambercy, "Design and Characterization of a Lightweight and Fully Portable Remote Actuation System for Use with Hand Exoskeleton," JIEEE ROBOTICS AND AUTOMATION LETTERS, vol. 1, no. 2, pp.976-980, 2016.
- [6] Turnip, A. and Hong, K.-S., "Classifying mental activities from EEG-P300 signals using adaptive neural network," International Journal of Innovative Computing, Information and Control, vol. 8, no. 9, pp. 6429-6443, 2012.
- [7] Khan, M. J., Hong, M. J., and Hong, K.-S., "Decoding of four movement directions using hybrid NIRS-EEG brain-computer interface," Frontiers in Human Neuroscience, vol. 8, Article no. 244, pp. 1-10, 2014.
- [8] Khan, M. J., Hong, K.-S., Naseer, N., Bhutta, M. R. and Yoon, S. H., "Hybrid EEG-NIRS BCI for rehabilitation using different brain signals," Proceedings of Annual Conference of the Society of Instrument and Control Engineers (SICE) 2014, Sapporo, Japan, pp. 1768-1773, 2014.
- [9] Krebs H, Hermano Igo, et al, "24 A Wrist Extension for MIT-MANUS", Journal of Advances in Rehabilitation Robotics, vol.306, pp.377-390, 2010.
- [10] Songyuan Zhang, Shuxiang Guo, Baofeng Gao, Qiang Huang, Muye Pang, Hideyuki Hirata and Hidenori Ishihara, "Muscle Strength Assessment System using sEMG-Based Force Prediction Method for Wrist Joint," Journal of Medical and Biological Engineering (JMBe), DOI:10.1007/s40846-016-2112-5, vol.36(1), pp.121-131, 2015.
- [11] Song Z, Guo S, Pang M, et al, "ULERD-based Active Training for Upper Limb Rehabilitation," Proceedings of the 2012 IEEE International Conference on Mechatronics and Automation (ICMA), pp.569-574, 2012.
- [12] Talha Shahid, Umar S Khan, "Design of a Low Cost Multi Degree of Freedom Hand Exoskeleton," Proceedings of 2014 International Conference on Robotics and Emerging Allied Technologies in Engineering(iCREATE), pp.312-316, 2014.
- [13] Marco Cempini, "A Powered Finger-Thumb Wearable Hand Exoskeleton With Self-Aligning Joint Axes," Proceedings of the 2015 IE/ASME Transaction on Mechatronics, pp. 705-716, 2015.
- [14] Wang P., "Research on the Manipulator System or Functional Rehabilitation of Finger Injuries," MS thesis, Harbin Institute of Technology, pp.1-18, 2011.
- [15] Muye Pang, Shuxiang Guo, Qiang Huang, Hidenori Ishihara, Hideyuki Hirata, "Electromyography-Based Quantitative Representation Method for Upper-Limb Elbow Joint Angle in Sagittal Plane," Journal of Medical and Biological Engineering(JMBe), vol.35, issue.2, pp.165-177, 2015.
- [16] Shuxiang Guo, Fan Zhang, Wei Wei, Fang Zhao, Yunliang Wang, "Kinematic Analysis of a Novel Exoskeleton Finger Rehabilitation Robot for Stroke Patients," Proceedings of 2014 IEEE International Conference on Mechatronics and Automation, pp.924-929, August 3-6, Tianjin, China, 2014.