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Kinematic Analysis of a Novel Exoskeleton Finger Rehabilitation Robot for Stroke Patients

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***Abstract* –The exoskeleton robot technology is more and more used in the assisting stroke patients in implementing rehabilitation training. In this paper, a novel exoskeleton finger robot has been described to aim at helping varieties of hemiparalysis patients recover motor function. The robot system adopts the EEG control and mainly consists of exoskeleton finger robot, EEG system, HMI system, motor controllers unit, some sensors and a workstation. And the hand exoskeleton mechanism is portable, wearable and adjustable for patients doing home rehabilitation training. Base on the Denavit-Hartenberg (DH) parameters method, the kinematic model of finger has built to be used in designing the robot. Through the simulation software ADAMS (Automatic Dynamic Analysis of Mechanical Systems), the parameters of position, velocity and acceleration (PVA) in each joint are simulated. From the result, it can view that the robot has high movement ability to finish the Continuous Passive Motion (CPM). Besides, a comparison test is done to study whether there are some motion blocks in wearing exoskeleton robot. Form the curve figure, in the two situations, the angle range of the MCP (metacarpaophalangeal) joint is equal, which verifies the interference of robot is small. These experiments demonstrate the exoskeleton can provide high efficiency movement ability for stroke doing the rehabilitation. In the future, with the optimization design, the robot will improvement and has a bright application prospect in the rehabilitation field.**

Index Terms - Exoskeleton finger robot, Rehabilitation, Kinematic simulation analysis

I. INTRODUCTION

As we know, the hand is key and indispensable part for human in the daily activities. However, hands, because of their special bone features, are easily injured and lose the motion function in the stroke, accident and so on. So in the medical profession, some therapists see the motor function recovery situation of the finger as a key criterion for upper limb rehabilitation [1].

However, as the increasing of stroke patients, traditional rehabilitation methods can't meet the needs of patients. Therefore, base on the Continuous Passive Motion (CPM) [2], some researches combine the robotic technology with rehabilitation medicine to use exoskeleton rehabilitation robot-assisted patients to recover motor function. According to the ergonomic design, exoskeleton finger rehabilitation robots provide an outer layer bone for patients' hand, and they can not only support protection for the patients' hand, but also assist patients to implement rehabilitation training. So there are many countries and institutions that have began to study this type robot in recent decade. In the 2005, Marcello Mulas developed a hand exoskeleton device based on the EMG signals to help people who have partially lost the ability to control correctly the hand musculature. It could help patient finish performing the setting task [3]. In the 2010, Shahrol Mohamaddan used the wire-driven mechanism to perform the finger extension and flexion movement. The device was simple structure and light weight, but its manner of dress was too complex for patients [4]. In the American, 2010, Sasha Blue Godfrey studied the Hand Exoskeleton Rehabilitation Robot (HEXORR) that had the capability to assist patients in opening the paretic hand and compensate for tone. This system could provide free movement and restrict movement by interactive virtual reality game to enhance user motivation and training effect [5]. In China, same schools are also devoting to the study of the exoskeleton hand rehabilitation. For instance, in the Hong Kong Polytechnic University, 2010, K.Y.Tong researched a novel design of a hand functions task training robotic system for stroke rehabilitation. The robot hand had five 5 individual finger assemblies capable to drive 2 degrees of freedom (DOFs) of each finger at the same time by using embedded EMG controller [6]. In the Beihang University, Jiting Li developed the iHandRehab that was comprised of exoskeletons for the thumb and index finger in the 2011. The device provided 4 DOFs for each finger through some parallelogram mechanisms. By the design features, joints of the device and their corresponding finger joints have the same angular displacement [7].

Through these exoskeleton hand robots have many advantages for enough range of motion and smart mobility, as well as scientific and effective evaluation system, most of the finger robots need to design separated device drivers, and their structures are usual so large that can't realize family rehabilitation. In addition, these robots are more complex and have no portability. In our previous work [8], an exoskeleton hand robot is designed to achieve four fingers flexion and extension together.

In this study, a novel finger exoskeleton rehabilitation device has been proposed and designed. The rest part of this paper is organized as follows. In section II, the system structure and the rehabilitation processing are introduced.

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Than according to the human finger stone characteristic, the kinematic model of the finger is built by Denavit-Hartenberg (D-H) parameters method in section III. By the experiment, some kinematic parameters of the finger robot are simulated in section IV. The final part is the conclusion for the whole paper.

II. SYSTEM STRUCTURE

A. *The rehabilitation system structure*

The rehabilitation system mainly consists of exoskeleton finger robot, EEG system, HMI system, motor controllers unit, some sensors and a workstation in Fig. 1.

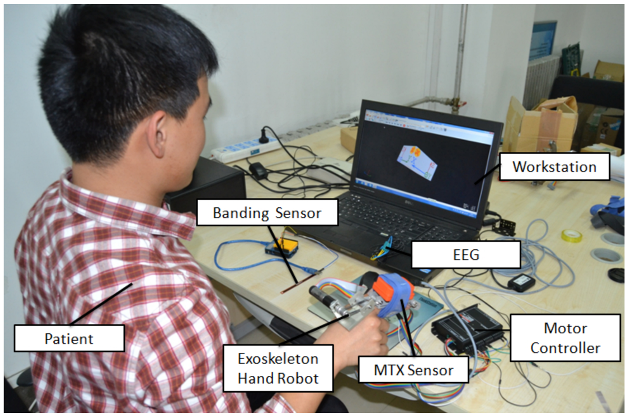


Fig. 1 The image of main parts in the rehabilitation system

In the processing of the rehabilitation training (Fig. 2), the exoskeleton hand robot is fixed on the patients' paralysation finger. When the HMI (Human Machine Interface) system sends visual stimulation signal to patients, their brains produce some EEG signals. The EEG (electroencephalogram) system collects and analyse these signals to send into the workstation for controlling the motor, which is fixed on the exoskeleton hand device. Meanwhile the bending sensor gets the motion angles of the device, and the force sensor is used to keep safety and obtain the force information in the training. By using the inertia sensor, therapists can obtain the movement information of hand device to set up better training method for patients [9], [10].

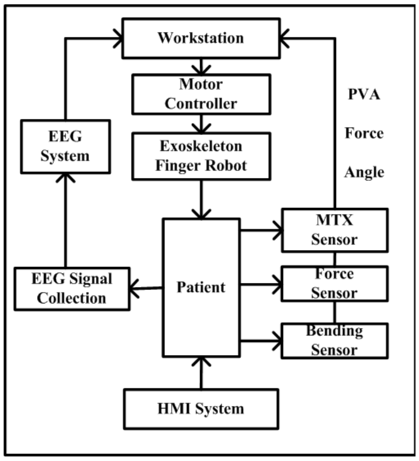


Fig. 2 The schematic of the processing of the rehabilitation training

B. *Motor controller unit*

In the exoskeleton finger device, the BLDC motor (Maxon) is used as the drive device to implement the finger flexion and extension movement. The motor is large torque of 23.5 Nm beyond the common human finger torque of 3.2Nm and high level integration that mainly consists of recommended electronics, reducer and controller. It is small with the size of 70×8 mm ($L\times R$) and light with only 23g, so it is very suitable to apply to the exoskeleton rehabilitation robot.

C. *MTX sensor*

The MTX sensor, which is a size of $38\times 53\times 21(W\times L\times H)$ and a weight of 30g, is used as a inertial orientation tracker unit for collecting dynamic movement information, including position, velocity and acceleration (PVA) [11]. In the sensor, three-dimension magnetometers with an embedded processor capable of calculating roll is assembled to calculate the angle of exoskeleton hand robot around the three axes at any time.

D. *Bending sensor*

The bending sensor (Spectra Symbol) is comprised of a flexible circuit board, force sensor, and elastic packaging materials. Through connecting the signal processing circuit, it can be applied in the situation that when the exoskeleton finger robot flexion or extension, the senor can measure its bend angle. Besides, it is so light and thin that can be directly attached to the robot structure.

III. DESIGN OF THE MECHANISM

A. *Structure of human hand*

The structure of human hand is mainly composed of bone, ligament, muscle, soft tissue and skin, which is very precise and complicated [12]. It has a total of 21 degrees of freedom to finish the daily activates (Fig. 3). The thumb has 5 DOFs that interphalangeal (IP) joint and 1 MCP (metacarpaophalangeal) joint are each 1 DOF, and carpometacarpal (CMC) joint is 3 DOFs. Except the thumb, the other fingers' structures are same, which have 2 DOFs in the MCP joint, 1 DOF in the PIP (proximal interphalangeal) joint and 1 DOF in the DIP (distal interphalangeal) joint

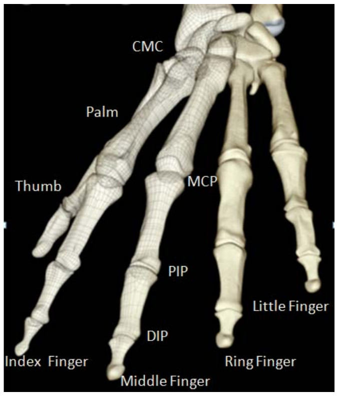


Fig. 3 The image of the bone structure of the hand

Because of this structure features, each finger can complete two motions that are flexion/extension and adduction/abduction motions. The motion constraints are mainly two kinds. The first is caused due to the physiological structure of the hand movement, and the motion range of finger is shown in Table I. Another kind is the coupler constraint in the process of hand movement. For instance, when the MCP joint of index finger is flexion, the middle finger also present a few bend in the MCP joint. According the Lee's study [13], in the movement process, the angles of DIP joint and PIP joint of each finger may exist in a constraint relation as follow:

$$\theta_{DIP} = 0.46\times\theta_{PIP} + 0.083\times\theta_{PIP}^2 \qquad (1)$$

TABLE I
RELATIVE PARAMETERS OF THE HAND

Joint	MCP	PIP	DIP	CMC
Flexion/Extension (Degree)	0~90	0~110	0~90	----
Adduction/Abduction (Degree)	-15~15	----	----	0

B. *Build the kinematic model of hand*

In this part, the kinematic model of finger is built by using DH parameters method. According the characteristics of the fingers, the index finger is selected as an example to built model, which has 4 DOFs and can be saw as a model of composing of three links in the Fig. 4 [14]. The coordinate system $x_0y_0z_0$, $x_1y_1z_1$, $x_2y_2z_2$, $x_3y_3z_3$ and $x_4y_4z_4$ respectively represent the rotation axes of MCP-1 joint (adduction/abduction), MCP-2 joint (flexion/extension), PIP joint , DIP joint and end effector of finger . Meanwhile, the coordinate system $x_0y_0z_0$ is also representation of the base coordinate system. The relationship between each link coordinate system is shown in Table II.

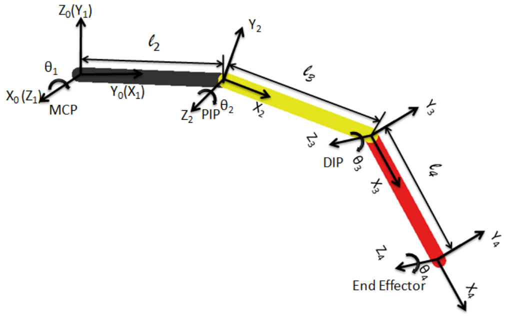


Fig.4 The drawing of the three links model of the finger

TABLE II
SOME PARAMETERS OF THE THREE LINKS MODEL

Joint	θ_i (°)	d_i (mm)	l_i (mm)	α_i (°)
MCP-1	---	--	--	--
MCP-2	θ_1	0	0	90
PIP	θ_2	0	l_2	0
DIP	θ_3	0	l_3	0
End Effector	θ_4	0	l_4	0

Where θ_i and α_i are the rotation angle of joints and torsion Angle, and d_i and l_i are the distances of the offset and the links.

Because of the need of the mechanism design of the exoskeleton robot, the impact of the MCP-1 is ignored. Therefore, according the DH parameters method, the transformation matrix between each links is as follow [15]:

$$^{i-1}T_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & l_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & l_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (2)$$

So the transform matrix from T_1 to T_4 can be obtained with parameters in Table II.

$$T_1 = \begin{bmatrix} \cos\theta_1 & 0 & \sin\theta_1 & 0 \\ \sin\theta_1 & 0 & -\cos\theta_1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (3)$$

$$T_2 = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & l_2\cos\theta_2 \\ \sin\theta_2 & \cos\theta_2 & 0 & l_2\sin\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (4)$$

$$T_3 = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & l_3\cos\theta_3 \\ \sin\theta_3 & \cos\theta_3 & 0 & l_3\sin\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (5)$$

$$T_4 = \begin{bmatrix} \cos\theta_4 & -\sin\theta_4 & 0 & l_4\cos\theta_4 \\ \sin\theta_4 & \cos\theta_4 & 0 & l_4\sin\theta_4 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (6)$$

Therefore, the transform matrix form the end effector of finger to the base coordinate system can be obtained as follow:

$$^{0}T_4 = T_1T_2T_3T_4 = \begin{bmatrix} \mathrm{c}_1c_{234} & -c_1s_{234} & s_1 & c_1\left(l_2c_2 + l_3c_{23} + l_4c_{234}\right) \\ s_1c_{234} & -s_1s_{234} & -c_1 & s_1\left(l_2c_2 + l_3c_{23} + l_4c_{234}\right) \\ s_{234} & c_{234} & 0 & l_2s_2 + l_3s_{23} + l_4s_{234} \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (7)$$

Where s_{234} refers to $\sin(\theta_2+\theta_3+\theta_4)$, and c_{234} refers to $\cos(\theta_2+\theta_3+\theta_4)$, and s_{23} refers to $\sin(\theta_2+\theta_3)$,and c_{23} refers to $\cos(\theta_2+\theta_3)$, and s_1, c_1, s_2, and c_2 refer to $\sin\theta_1$, $\cos\theta_1$, $\sin\theta_2$ and $\cos\theta_2$ respectively.

According to the transform matrix principle,

$$^{0}T_4 = \left[\begin{array}{c:c} T_R & T_P \\ \hdashline 0 & 1 \end{array}\right] \qquad (8)$$

So the position of any point of the end effector of finger can be obtained

$$T_P=\begin{bmatrix} c_1\left(l_2c_2+l_3c_{23}+l_4c_{234}\right) \\ s_1\left(l_2c_2+l_3c_{23}+l_4c_{234}\right) \\ l_2s_2+l_3s_{23}+l_4s_{234} \end{bmatrix} \tag{9}$$

$$\begin{cases} P_X=c_1\left(l_2c_2+l_3c_{23}+l_4c_{234}\right) \\ P_Y=s_1\left(l_2c_2+l_3c_{23}+l_4c_{234}\right) \\ P_Z=l_2s_2+l_3s_{23}+l_4s_{234} \end{cases} \tag{10}$$

Through taking the partial derivatives of the rotation angles of the joint, the Jacobian matrix of the index finger is indicated below,

$$J\left(\theta_1,\theta_2,\theta_3,\theta_4\right)=\begin{bmatrix} \frac{\partial p_x}{\partial \theta_1} & \frac{\partial p_x}{\partial \theta_2} & \frac{\partial p_x}{\partial \theta_3} & \frac{\partial p_x}{\partial \theta_4} \\ \frac{\partial p_y}{\partial \theta_1} & \frac{\partial p_y}{\partial \theta_2} & \frac{\partial p_y}{\partial \theta_3} & \frac{\partial p_y}{\partial \theta_4} \\ \frac{\partial p_z}{\partial \theta_1} & \frac{\partial p_z}{\partial \theta_2} & \frac{\partial p_z}{\partial \theta_3} & \frac{\partial p_z}{\partial \theta_4} \end{bmatrix}$$

$$=\begin{bmatrix} -s_1M & -c_1N & -c_1H & -c_1K \\ c_1M & -s_1N & -s_1H & -s_1K \\ 0 & M & I & Q \end{bmatrix} \tag{11}$$

Where,

$$\begin{cases} M=l_2c_2+l_3c_{23}+l_4c_{234} \\ N=l_2s_2+l_3s_{23}+l_4s_{234} \\ H=l_3s_{23}+l_4s_{234} \\ I=l_3c_{23}+l_4c_{234} \\ K=l_4s_{234} \\ Q=l_4c_{234} \end{cases} \tag{12}$$

Namely,

$$\begin{bmatrix} \mathrm{d}_x \\ d_y \\ d_z \end{bmatrix}=\begin{bmatrix} -s_1M & -c_1N & -c_1H & -c_1K \\ c_1M & -s_1N & -s_1H & -s_1K \\ 0 & M & I & Q \end{bmatrix}\begin{bmatrix} d_{\theta_1} \\ d_{\theta_2} \\ d_{\theta_3} \\ d_{\theta_4} \end{bmatrix} \tag{13}$$

Equation (13) reflects the motion position of the finger. Making (13) divided the d_t can get the velocity relation of the finger.

$$V=\begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix}=\begin{bmatrix} -s_1M & -c_1N & -c_1H & -c_1K \\ c_1M & -s_1N & -s_1H & -s_1K \\ 0 & M & I & Q \end{bmatrix}\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \\ \dot{\theta}_4 \end{bmatrix} \tag{14}$$

Namely, Equation (14) can be simplified as

$$V=J\dot{\theta} \tag{15}$$

In a similar way, the acceleration relation of the finger is same as

$$\mathrm{A}=J\ddot{\theta} \tag{16}$$

Based on the reversibility of Jacobi matrix, as long as given the rectangular coordinates speed of end effector of the finger, the speed of the corresponding joint can be got by the equation:

$$\dot{\theta}=J^{-1}V \tag{17}$$

B. The structure of the exoskeleton finger robot

According to ergonomic characteristics, the exoskeleton hand robot is designed in Fig. 5. It is a length of 146mm and weigh of 104g, so it can be dressed directly on the patients' paralysis hand. The materials of the robot are selected as nylon, copper and aluminum alloy. It is designed some adjustable length devices 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. For decreasing the size of the robot system, unlike others existing exoskeleton finger robot, this finger robot makes the drive device and execute device together so that increases the integration capability.

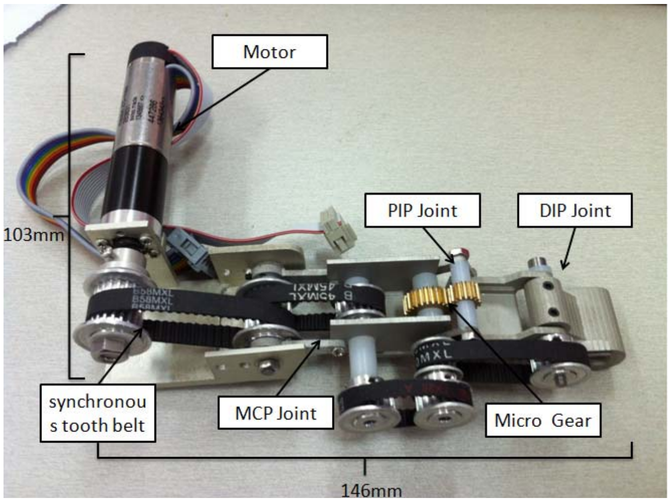


Fig.5 The drawing of physical map of the finger robot

The finger 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 in Fig 6. The mainly transmission ratio is decided as the 1 to 1 and 3 to 4 that can make the robot Smooth movement. Besides, in the PIP joint, two micro gears (transmission ratio 3 to 5) are used to achieve the joint flexion. Through synchronous belt transmission, motor transmits the drive force to the synchronous belt wheel in each joint to control their movements. Meanwhile, the bending sensor is attached on the robot to measure bending angles in the rehabilitation training.

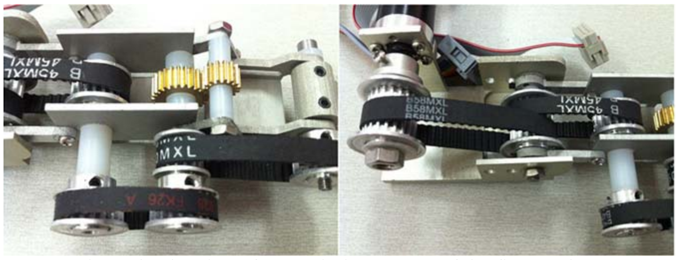
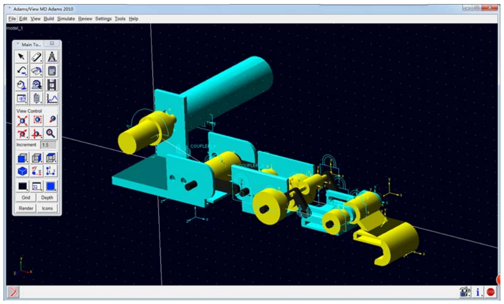


Fig.6 The drawing of transmission system of the finger robot

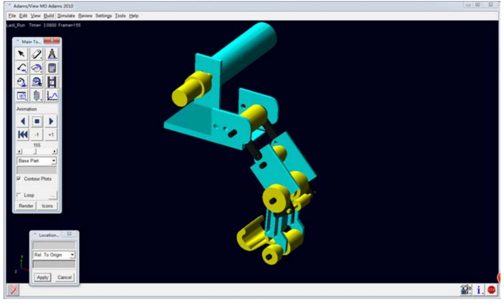
IV. EXPERIMENTAL SETUPS

A. The kinematic simulation of the exoskeleton hand robot by using ADAMS

In simulation software ADAMS, the virtual prototype of the exoskeleton finger robot is built as well in Fig. 7 (ignore the synchronous belt). Without the load influence, just the kinematic regulation of robot is discussed. The kinematic pairs add on the each part of the robot, including rotation joint, fixed joint and coupler pair. The drive function is inputted as "STEP (time, 0, 15d*time, 5, 75d) + STEP (time, 5, -15d*time, 10, -75d)", which is a 10s back and forth movement. Then by using the post-processing function of the ADAMS, the simulation result about the PVA parameters of the exoskeleton finger robot is displayed in the Fig. 8.

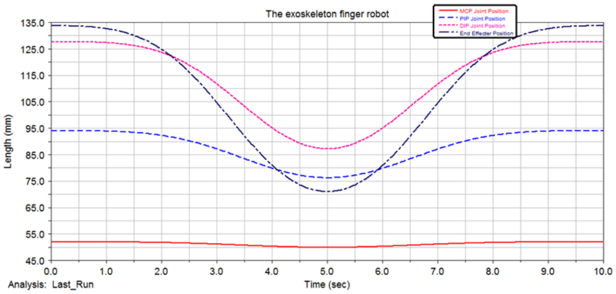


(a) Extension

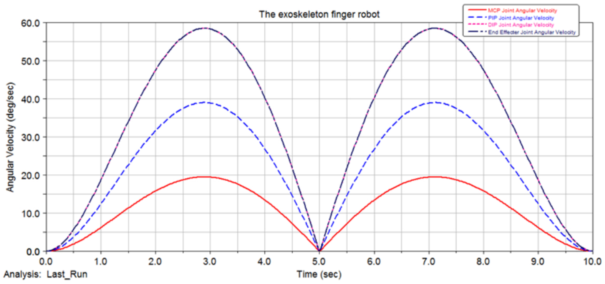


(b) Flexion

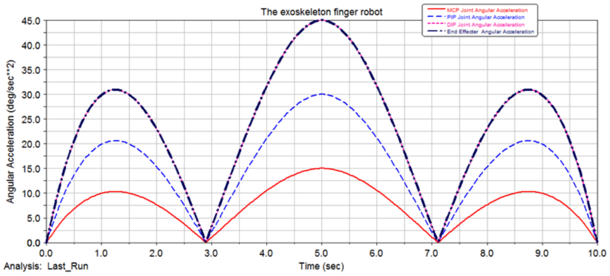
Fig.7 The image of ADAMS simulation of the exoskeleton finger robot



(a) The position image of the exoskeleton finger robot



(b) The angle velocity image of the exoskeleton finger robot.



(c) The angle acceleration image of the exoskeleton finger robot.

Fig.8 The image of the simulation result of the exoskeleton finger robot

From the result, in the motion, it can see that the exoskeleton finger robot has movement coherence without singular position and can assist patients to implement the flexion and extension movement. The displacement variation of the end effector position is largest. And the angle velocity and angle acceleration is change as time going. In the 2.7s, the angle velocities in each joint reach the maximum in DIP joint and end effector, and in the 5s, the angle acceleration reach also the maximum in DIP joint and end effector. According the curve characteristic, the movement has the symmetry.

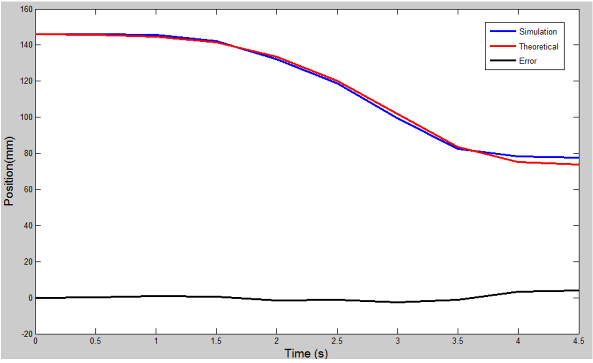
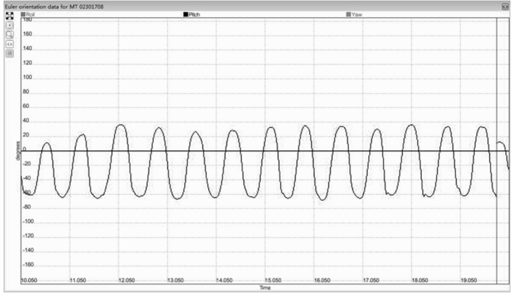


Fig.9 The image of the end effecter position curve

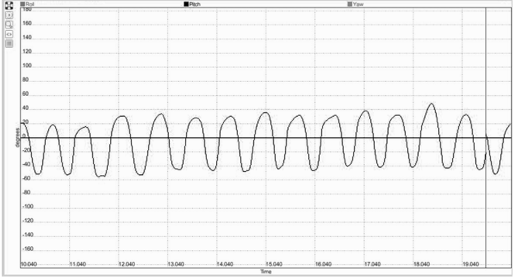
According the angles of each joint in the special time by ADMAS, the position values of simulation and theoretical in end effector is obtained and compared in Fig. 9. From the figure, it can see that the error values about the simulation and theoretical is little and distributed around the zero axe. So the kinematic analysis of the finger is verified.

B. The study of the motion block for the index finger with dressing the exoskeleton finger robot

In the experiment, two situations will be studied for testing the motion block of the exoskeleton finger robot. One is that people make flexion motion his finger without the robot, the other is not. In the two experiments, the MTX sensor is fixed on the MCP joint of the index finger. And the index finger finishes many times flexion and extension movement to monitor the angle change of the MCP joint. The result is shown in the Fig. 10. From the image, the motion range of the MCP joint without the robot is from the -38° to 68°, and the other is from -37° to 57°. It can be obtained that whether or not dressing the exoskeleton finger robot has a small impact on movement range of the finger. Therefore, the exoskeleton robot can give the suitable auxiliary for patient finishing the rehabilitation training.



(a) The flexion angle of the index finger without robot



(b) The flexion angle of the index finger with robot.

Fig.10 The contrast figure of movement ability with dressing the robot

V. CONCLUSION AND FUTURE WORK

In this paper, a novel exoskeleton finger robot is proposed to assist the stroke patients to recovery the motion function of finger. The mechanism, which is portable and wearable for patients doing home rehabilitation training, has 3 DOFs movement to achieve flexion/extension movement. In the experiment, through the simulation software ADAMS, the PVA parameters in the three joint has been simulated. Besides, the motion ability of dressing the robot is tested. From the above, researches, some conclusion are summed up as follow:

1) The exoskeleton finger robot has movement coherence without singular position in each joint.
2) The displacement variation of the end effector position is relatively largest.
3) The exoskeleton finger robot has suitable wearability and movement ability to meet patients' rehabilitation training.

In the future work, we will add thumb mechanism to achieve the whole hand motion. Meanwhile, by changing the transmission method increases movement fluent ability of the robot to better assist patients in rehabilitation training. And 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.

REFERENCES

[1] Yang E, et al. "Carotid arterial wall characteristics are associated with incident ischemic stroke but not coronary heart disease in the Atherosclerosis Risk in Communities (ARIC) study", Journal of Stroke, Vol.43, No.1, pp.103-108, 2012.

[2] Postel J M, Thoumie P, Missaoui B, et al. "Continuous passive motion compared with intermittent mobilization after total knee arthroplasty. Elaboration of French clinical practice guidelines", Journal of Annales de réadaptation et de médecine physique, Vol.50, No.4, pp.251-257, 2007.

[3] Mulas M, Michele F. "An EMG-controlled exoskeleton for hand rehabilitation", Proceedings of the 2005 IEEE International Conference on Rehabilitation Robotics (ICORR), pp.371-374, 2005.

[4] Mohamaddan S, Komeda T. "Wire-driven mechanism for finger rehabilitation device", Proceedings of the 2010 IEEE International Conference on Mechatronics and Automation (ICMA), pp.1015-1018, 2010.

[5] Godfrey S B, Schabowsky C N, et al. "Hand function recovery in chronic stroke with HEXORR robotic training: A case series", Proceedings of the 2010 IEEE International Conference on Engineering in Medicine and Biology Society (EMBC), pp.4485-4488, 2010.

[6] Tong K Y, et al. "An intention driven hand functions task training robotic system", Proceedings of the 2010 IEEE International Conference on Engineering in Medicine and Biology Society (EMBC), pp.3406-3409, 2010.

[7] Jiting Li, et al. "iHandRehab: An interactive hand exoskeleton for active and passive rehabilitation", Proceedings of the2011 IEEE International Conference on Rehabilitation Robotics (ICORR), pp.1-6, 2011.

[8] Wei Wei, Shuxiang Guo, Fan Zhang, et al. "A novel upper limb rehabilitation system with hand exoskeleton mechanism", Proceedings of the 2013 IEEE International Conference on Mechatronics and Automation (ICMA), pp.285-290, 2013.

[9] Tsai, et al "An Articulated Rehabilitation Robot for Upper Limb Physiotherapy and Training", Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, pp.1470-1475, 2010.

[10] Shuxiang Guo, Fan Zhang, Wei Wei, et al. "Development of force analysis-based exoskeleton for the upper limb rehabilitation system", Proceedings of the 2013 IEEE International Conference on Complex Medical Engineering (CME), pp. 285-289, 2013.

[11] Zhibin Song, Shuxiang Guo, Yili Fu. "Development of an Upper Extremity Motor Function Rehabilitation System and an Assessment System", International Journal of Mechatronics and Automation, Vol.1, No.1, pp.19-28, 2011.

[12] Lee J W. "Rim K. Maximum finger force prediction using a planar simulation of the middle finger", Journal of Engineering in Medicine, Vol.204, No.3, pp.169-178, 1990.

[13] Peng Wang. "Research on the Manipulator System or Functional Rehabilitation of Finger Injuries", MS thesis, Harbin Institute of Technology, pp.1-18, 2011.

[14] Meili Yu, et al. "Kinematics Analysis of Exoskeletons Rehabilitation Robot Based on ADAMS", Proceedings of the 2012 IEEE International Conference on Man-ufacturing Science and Engineering (ICMSE), pp.2333-2338, 2012.

[15] Shuxiang Guo, Wei Wei, Wu Zhang et al. "A kinematic model of an upper limb rehabilitation robot system", Proceedings of the 2013 IEEE International Conference on Mechatronics and Automation (ICMA), pp. 968-973, 2013.