A Finger Exoskeleton for Rehabilitation and Brain Image Study

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Abstract—**This paper introduces the design, fabrication and evaluation of the second generation prototype of a magnetic resonance compatible finger rehabilitation robot. It can not only be used as a finger rehabilitation training tool after a stroke, but also to study the brain's recovery process during the rehabilitation therapy (ReT). The mechanical design of the current generation has overcome the disadvantage in the previous version[13], which can`t provide precise finger trajectories during flexion and extension motion varying with different finger joints` torques. In addition, in order to study the brain activation under different training strategies, three control modes have been developed, compared to only one control mode in the last prototype. The current prototype, like the last version, uses an ultrasonic motor as its actuator to enable the patient to do extension and flexion rehabilitation exercises in two degrees of freedom (DOF) for each finger. Finally, experiments have been carried out to evaluate the performances of this device.**

Keywords—finger rehabilitation; MRI compatible; brain image; ultrasonic motor;

I. INTRODUCTION

After a stroke, most survivors have impaired motor function. Rehabilitation robotics are usually employed to provide highly repetitive, task specific movements without the high cost and labor burden occurred in conventional one on one therapy [1][2]. However, during traditional robotic therapies, there is little specific information acquired about the brain activity related to the improvement of the motor function. Therefore, it is a big technological challenge to objectively evaluate the specific effects of ReT.

The appearance of functional Magnetic Resonance Imaging (fMRI) offers an objective approach to identify changes in brain activity during or after ReT. Thus, combining robotics technology and fMRI to implement rehabilitation therapy has been seen as a critical method in new rehabilitation research [3][4][5]. Meanwhile, studying the specified reorganization area of the brain during the therapy could help researchers to understand how the motor processes are relearned, which might gain significant insight into stroke recovery therapy.

Furthermore, during the ReT process, motivation has been seen as an important factor and frequently used as a determinant of the rehabilitation outcome [6]. Though, there is no consensus on what kind of training strategies are more motivating than others. Using fMRI to study the particular brain regions involved in rehabilitation learning under different training strategies might help physiotherapist to tailor out an optimized, motivating “training menu” for their patients.

For the strong static magnetic field in an MRI machine, conventional actuators and mechatronics components are not suitable to be used inside. The device exposed in it should meet with two significant factors [7][8]. Firstly, all the components should have zero inherent magnetization; secondly, they should have negligible effect on the quality of the image. Therefore, developing an MRI compatible robot (MRICR) is challenging.

By now several MRI compatible surgical robots and rehabilitation devices have been reported. In [4] an MRI compatible haptic interface was introduced, which was used to study the neural control of human motion. This robot was powered by a master-slave actuator. It used a conventional actuator placed outside the scanner room and a hydraulic connection to transmit the force and motion to a magnetically inert slaver placed close to or inside the MRI scanner. The experimental results showed that the system was able to perform movements with high accuracy and with forces up to several thousand Newton.

An fMRI compatible robot that was able to perform a number of predefined knee movements has been developed at ETH Zurich [9]. This robot was actuated by two pneumatic cylinders to overcome the magnetic problem of conventional actuators. In a pilot study, the authors observed the brain activity with MRI under three different training strategies during the knee joint movement. The result revealed that there was a tendency towards more activity in the motor/sensory network the more “challenged” the subject were, which verified their hypothesis that error amplification strategies appear to have a great potential to improve robotic therapy outcomes.

Another one DOF, MR compatible hand rehabilitation device was introduced in the literature [8]. This device was developed for fMRI studies of the brain and motor performance during rehabilitation after stroke. The key feature

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of this device is the use of electro rheological fluids (ERF) as the power generating source, as a replacement for traditional actuators. The ERF is a fluid which rheological property dramatic changes when exposed to an electric field. Thus, it can generate controllable resistive torques corresponding to different electric voltages. The author also verified the MRI compatibility of the ERF. Due to the use of this power source, the system was portable. However, only closing of the hand could be trained with this system.

In our research, we intend to develop an MRI compatible hand rehabilitation device, which should not only be competent as a hand rehabilitation device for stroke patients, but could also be able to provide abundant functions in studying the relations between brain image and ReT process in an MRI machine.

Compared with other MRI compatible device, the development of an MRI compatible rehabilitation device for individual fingers poses several challenges. Firstly, the size of the actuator and sensor should be small due to the necessity of several actuators and sensors in a compact package (a small overall size is preferential for portability reasons). Secondly, due to the complicated bone structure of the human's hand, it is quite difficult to create a device that can provide rehabilitation function for each single joint. Although the master-slave actuator driving strategy developed in [4] meets their requirements, such a system has very limited portability and high space demands. Similarly, an hydraulic cylinder or pneumatic cylinder [9] needs a liquid or air compressor as well as control valves, which are also relatively big volume. After an overall consideration, in our research we use an ultrasonic motor as the actuator, which can output high torques with a relative small size, to achieve our small size requirement.

Another challenge for a small size finger rehabilitation device is the complex structure of the human's hand. There are more than twenty DOF for each hand, so if the goal is to develop a hand rehabilitation robot that can control each joint independently, the number of necessary actuators will result in a large volume even when using a relative small size ultrasonic motor. The literature [10] describes a hand function training robot which detects the intention (opening or closing) from the stroke person, using the electromyography (EMG) signals measured from the hemiplegic side of the arm. Each hand has 5 individual finger assemblies capable to drive 2 joints of each finger at the same time, powered by one linear actuator. This design shows that one actuator can be used effectively in rehabilitation tasks to drive two joints of one finger. In general, coupling of joints provide a possibility to reduce the size of hand exoskeletons. Nevertheless, the robot described in [10] has two limitations. The first is that the exoskeleton's joint centers are irrespective of the corresponding joint angle of the human. Instead it would be beneficial if the joint center of the exoskeleton adapts to the joint angle of the human hand. The other disadvantage is that the design cannot adjust for a wide range of different human fingers' length. These problems also exist in the robot described in [11].

As a conclusion, few rehabilitation devices exist that are MRI compatible. Out of those, none can provide movements for individual fingers. Moreover, in many hand exoskeletons the joint centers are irrespective of the corresponding humans' joint angle and the device cannot adjust for a wide range of different human fingers' length. Therefore, we developed out an MRI compatible hand rehabilitation robot that can satisfy all those functions [13]. However, in our previous prototype, the finger driving mechanism is composed of five links, which has a possible to produce different trajectories for the finger during flexion and extension motion. Nevertheless, it would be advantageous if the trajectory of the finger could be precisely defined. Therefore, it lead to the design of our new prototype, see Fig.1.

This paper is arranged as follows: Section II describes the mechanical design. Section III presents three different working modes of the device. Section IV details the control system. Section V evaluates the performance. Conclusions and future works are addressed in Section VI.

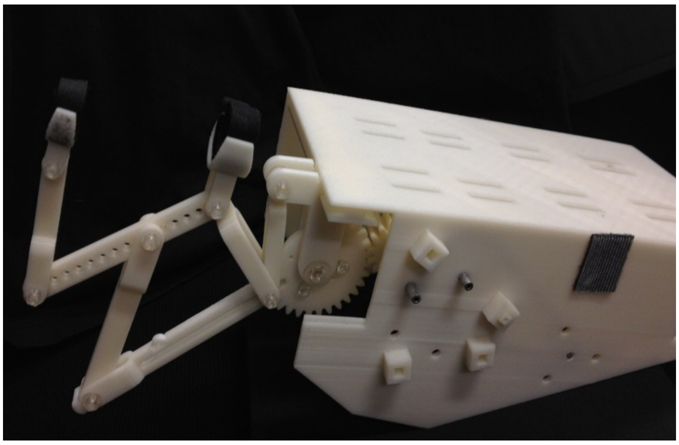


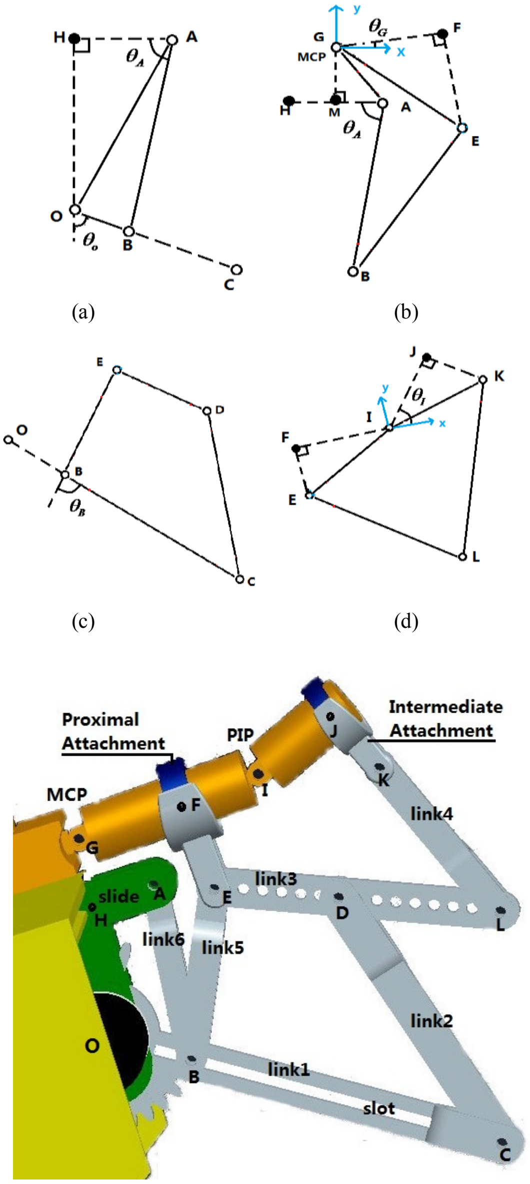
Fig. 1. The second generation prototype of a finger rehabilitation robot

II. MECHANIC DESIGN

As mentioned above, in our previous prototype, we adopt five links to achieve that one actuator drives two joints' (MCP and PIP) extension and flexion motion. It can provide enough torque to finish the required motion and can reach the full range of motion (ROM) on the MCP joint and the PIP joint, respectively. On the negative side, the five links result in two DOF, therefore the system is underactuated. In other words, there are different possible trajectories for the finger during flexion and extension. It would be advantageous if the trajectory of the finger could be precisely defined. Therefore, in our new prototype, we developed a novel six links driving mechanism which is composed of three four-link mechanisms and one three-link mechanism to overcome this shortage.

A. Finger joint driving mechanism

The design of the current generation is presented in Fig. 2. It is composed of six links, two attachments and one slide. Link 1 is rotated by the actuator. One side of link 5 and link 6 are synchronized to slide on slot in the link 1. Each attachment is worn on the finger's proximal and intermediate segment, respectively, which are connected by link 3 and link 4. The slide is used as a base to support the rotating motion for one side of the link 1 and the link 6. The quadrangle BAHO can be simplified as triangle BAO since the length and relative angle of AH and HO is constant. Similarly, the hexagon BEFGHA and hexagon LKJIFE also can be simplified into quadrangle BEGA and LKIE separately. Therefore, this six links mechanism can be seen as one three-link mechanism and three four-link mechanisms, see Fig.2.(a)(b)(c)(b). As both the three-link and four-link mechanisms are one DOF mechanism, thus, it result the six-link mechanism into one DOF, which means it enable us to calculate each single joint's angle and torque base on the velocity and torque transferred from the motor. θ_G is the MCP joint angle and θ_I is the PIP joint angle.



(a) (b)

(c) (d)

Fig. 2. Finger driving mechanism

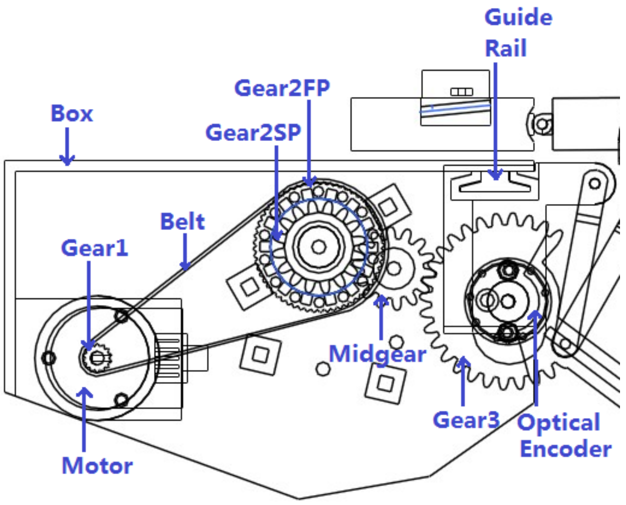


Fig. 3. Power transferring system

The length for each link is primarily decided base on the ROM of the MCP joint and the PIP joint, which have been set to 0°~90° and 0°~110° separately. Afterwards, it has been verified by the maximum torque needed to drive two joints for one finger. (the ROM and torque for each finger joint are presented in our previous research [14]).

B. Power providing system

The actuator for each finger is an ultrasonic motor (SHINSEI USR30E3N) (see Fig.3) with a size of 35 mm x 36 mm x 40 mm, including a build-in encoder. It has a high power-to-weight ratio, high precision in positioning, speed controllability, silent motion and is made of absolutely no magnetic materials. The maximum torque is 0.1 Nm, the maximum speed is 250 rpm, and the driving frequency is 50 KHz. On the contrary, since the ultrasonic motor is driven by frictional force between the stator and motor rotor, thus, it's inherent non-backdrivable. Additionally, the ultrasonic motor has a relative slow "start-up " (50 ms) and "stop" (1 ms) response time, which restrict it to be used in some high performance situations. Other drawbacks also include: temperature rise in case of long term using and a velocity dead band [15].

In this device the actuator is located away from the hand exoskeleton in a box under the palm, driving the extension or flexion motion for the MCP and PIP joint simultaneously. All the mechanical components are produced by ABS plastic materials through 3D printing technology. The MITSUBOSHI belt has been applied between two custom designed gears (Gear 2 FP and Gear 1) to transfer the power output from the motor. Finally, the whole power providing system fits into a small size of 22 cm x 12 cm x 11 cm.

C. *Adjust for various finger phalange lengths*

This device has been design to adjust for various finger phalange lengths and finger gaps. The proximal/intermediate attachment position can be freely worn on the proximal and intermediate finger segments, respectively. Meanwhile, the attached positions on the link 3 for the link 4 can be easily modified in terms of different finger phalange length. However, in very few cases the attachment palace for the link 2 on link 3 may need to be changed. Additionally, this device has been designed to adjust for different gaps between fingers, since all four slides are mounted on a Guide Rail, by slide them, the distance between fingers can be easily modified. The range for modify is nearly 15mm.

D. *Safety measures*

For human rehabilitation use, safety needs to have a high priority. In our device the safety measures mainly include three steps: firstly, the slot length in link 1 controls the range of motion for the link 5 and the link 6, which could preliminary ensure that the device won't move out of range even if the actuator is out of control. Secondly, in Gear 3 distributes several holes, before using the hand exoskeleton, we insert two pins into two of these holes to limit its maximum range of motion. Once the device out of control, the pins on Gear 3 could be the second protection to stop the power transfer when one of them contacts with any side of the slide. The last measure is an emergency power kill button, which could turn off the power for all hardware.

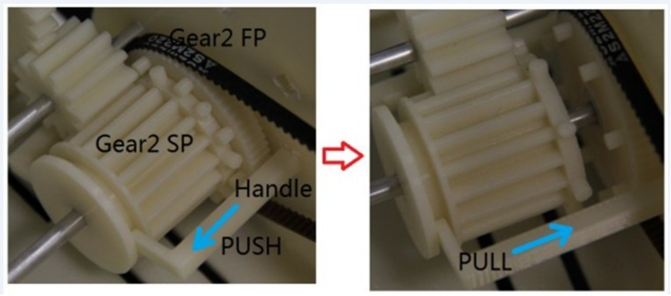
III. THREE WORKING MODES

In the current prototype, three working modes have been developed to meet various different requirements of finger ReT. Furthermore, these modes are expected to be used in the next stage of the research on studying the brain activities undergoing different training strategies.

A. *Passive mode and Active mode.*

In ReT, the passive mode is the one in which the robot forces the impaired parts of the body to move. On the opposite side, the active mode is the one in which subjects move their impaired body parts themselves inside robots to implement rehabilitation training. Literature [12] studied the brain representation of active and passive flexion/extension movement on the elbow with six healthy volunteers. During passive movement, the subject's right arm was driven by a torque motor inside a guide hinge, while, the active movement is the subjects active to move their elbow joints with the same amplitude and frequency as in passive mode. Regional cerebral blood flow (rCBF) was measured under these two training conditions. The results present that the rCBF in the contra-lateral sensori-motor cortex were strong increased both in the active and passive movements. In addition, they were identical in location, amount and extent. However, in the supplementary motor area, the rCBF was stronger in active condition than passive condition. Therefore, active mode plays a role as important as, or sometimes more important than passive mode on ReT.

However, developing an active mode in a device driven by an ultrasonic motor would be difficult because its inherent shortage of non-back drivability. In our research, we overcome this disadvantage by improving the mechanical design. One gear which can work in two modes, mesh or non-mesh was designed to solve this problem. The mesh or non-mesh state of this gear is controlled by a manual driving handle which inserts into the slot of the Gear2 SP. The Gear2 FP and Gear2 SP will separate when the handle is pushed in the opposite direction, and in this way the power from the motor is not passed to the links. Thus, the hand inside the exoskeleton could move freely, namely in active mode (Fig.4.b). On the contrary, when the handle is pulled in the same direction with Gear2 FP, the two gears mesh, causing the power output form motor forcing the finger to do rehabilitation, namely, passive mode (see Fig.4.a). During the passive mode, the build-in optical encoder can be used to feedback control the motor. Meanwhile, in Active mode, one optical encoder sensor (Fig.3) is used to monitor the patient's motion.



(a) (b)

Fig. 4. Passive and active mode

B. *Self-motion control mode.*

Considering most of the stroke patients are paralyzed in one half of their body. However, being actively engaged in rehabilitation exercise has been regarded as an important factor in motor function recovery. With that in mind, we developed the self-motion control mode for our device. This mode is fully under control of the subjects themselves, they use the health part body to control the motion on impaired part body through rehabilitation device. Since the subjects have to concentrate on their work during the whole process, it is reasonable to expect benefiting more than other unconscious work.

In this design, one 5DT(Fifth Dimension Technology company) Ultra_14 Data Glove was involved. This data glove is optimized for use in MRI environments. The glove itself does not contain any magnetic parts. The material of the sensors are black stretch lycraIt. In the Ultra_14 serial, 14 sensors integrated in one hand distributed on different finger joints (see Fig.5). However, in our design, we just use the sensors located on the MCP joint as the control signal to the

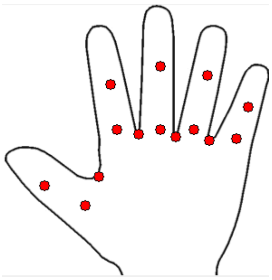


Fig. 5. Sensors' distribution in 5DT glove

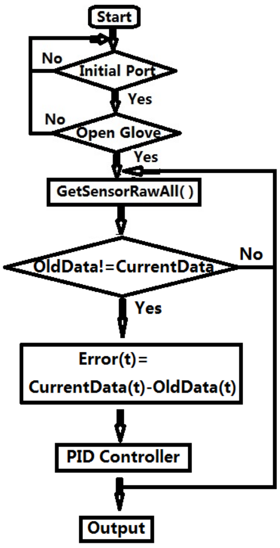


Fig. 6. Software diagram

device since the MCP and PIP joint are coupled. But the information gotten from the PIP joint sensor can also be used as a reference to design the links' parameters, which could enable us to get a more accurate finger trajectory. When switching to self-control mode, the subject wears this glove on his/her health hand, the glove collecting the finger's joint information in real-time with a frequency of 100 Hz. Old data and current data will be compared at the end of each cycle time, if there have differences, we consider it as the finger's movement, then this data will be used by the PID controller to control the motor (Fig.6).

IV. CONTROL SYSTEM

The control system for this robot is mainly composed of four parts: interface software in host computer, MCU (Micro Control Unit), 5DT data glove, device (robot). Fig.7. illustrates their connections.

The main controller for this robot is a high performance AVR real-time micro controller. It has an advanced RISC architecture. Most of the instructions are executed within a single clock cycle. Therefore, combined with a 16MHz working frequency, it can achieve real time control and sensor signal collection.

The communication between the host computer and the MCU is based on the RS232 protocol. Different tasks are identified by their header and end byte in a five bytes data package. Once the task has been confirmed, the program will execute the task base on the data information gotten from the second, third and fourth byte. For example, in the motor feedback control mode, the second byte indicates how many times to implement the extension and flexion motion, the third byte states the ROM on the MCP joint and the fourth byte transfers the speed control information.

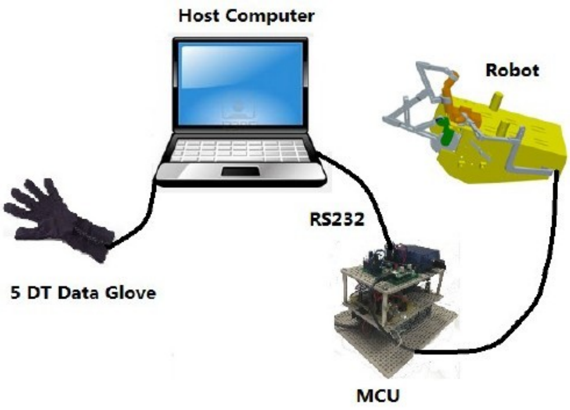


Fig. 7. Overview of the whole system

As mentioned above, the actuator for each finger is an ultrasonic motor, which is different from a typical electric motor. It consist of a rotor and a stator, the friction force between the rotor and the stator drives the motor to work. The control command to this motor is two sine signals (approximate 110V AC) with a phase difference which are converted from a 24V DC signal by the power output transformer part in the driver unit. When start to work, the driver gets the motor direction control signal (Start/Stop, CW/CCW) and speed modify signal from the MCU, simultaneously, the sensor (the motor build-in encoder in the Passive mode and the Self control mode or Optical encoder in the Active mode) feedbacks the position information to the MCU, thus, forming a position closed loop control.

V. PERFORMANCE EVALUATION

In order to evaluate the effectiveness of the new mechanical structure and also to verify the stability of the whole control system, two experiments have been carried out.

As described previously, our first generation prototype is designed by five-links, which may result in different solutions of the finger trajectories depending on the torque relations between the MCP joint and the PIP joint. In the current prototype, this problem has been addressed by the design of six-links, which is composed of one three-link mechanism and three four-link mechanisms. As long as the attachment positions and links' length are fixed, the finger's trajectory is determined. In other words, If we change the link's length or attachment position, different trajectories can be achieved according to the requirements. Fig.8. depicts the two finger joints' trajectories. It shows our device can provide the MCP joint and the PIP joint to do extension and flexion motion with a full ROM. The range of the MCP joint is approximately 0~88° as well as 0~109° on the PIP joint.

In the second experiment, a healthy subject wore two 5DT data gloves on both his hands. The subject was moving the middle finger of the right hand and the data glove measured the joint angles of the MCP joint. Those values were used to control the robot on the left hand. Meanwhile, the glove on the left side was used to record the trajectory of the finger motion

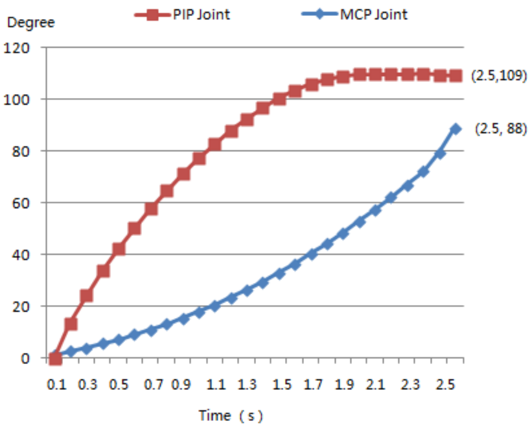


Fig. 8. The angle change on the MCP joint and the PIP joint

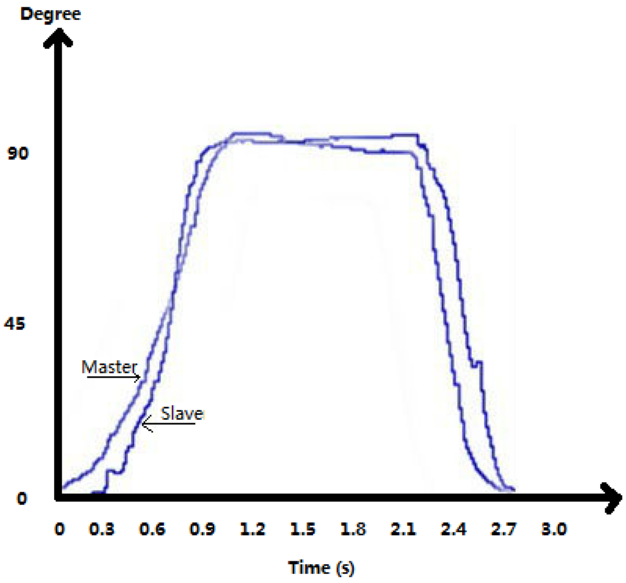


Fig. 9. The MCP joint angle trajectories on the master and slave hand

when it was driven to do the mirror motion. Fig. 9 shows the results of a subject did one time's extension and flexion motion. The graphs show the device has a good stability and accuracy on following the master motion, although there is a time delay of approximately 0.3 s, which may due to the relative slow response time of ultrasonic motor and the limitation of the interrupt time of the Windows operating system .

VI. CONCLUSION AND FUTURE WORK

This paper presents the second generation MRI compatible finger rehabilitation robot that was developed under consideration of the special requirements for clinical studies. Comparing with our previous prototype, current design could provide a more accuracy motion on the MCP joint and the PIP joint. Besides, three modes have been developed in this design, which are intended to studying the relations between brain activity and motor function inside an MRI machine .

The current work is a basis for future research work. The next step works will include verify the MRI compatibility of this device. Afterwards, studying the brain activities under different training strategies. Finally, using patient studies we hope to gain insights into the brain reorganization process during stroke recovery, leading to better ReT procedures.

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