Proceedings of 2017 IEEE
International Conference on Mechatronics and Automation
August 6 - 9, Takamatsu, Japan

Design and Evaluation of a 3-degree-of-freedom Upper Limb Rehabilitation Exoskeleton Robot

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***Abstract* - As an important branch of medical robot, rehabilitation training robot for hemiplegic upper limbs is a hot research topic. Based on motor relearning program, it covers many technology fields, such as rehabilitation medicine, human anatomy, mechanics, computer science, and robotics, etc .With the developing of auxiliary robot, there are still some disadvantages in the existent devices, such as heavy weight, few degrees of freedom, non-portable, low accuracy. These defects make it difficult for the rehabilitation robot to be applied to the actual rehabilitation practice. In this paper, we designed a rehabilitation robot with three DOFs. Compared to the previous device, this design can overcome some shortcomings which makes it flexible, portable, light weight, high accuracy and easy to wear. In this paper, the general structure of the flexible robot manipulator is introduced. The experiment is designed to test and analyse the error in its movement. The application of flexible transmission can greatly reduce the weight of the patient's arm, but may lead to errors in accuracy. Therefore, it is necessary to design experiments to test and analyse errors. The results show that the device can be easily and smartly dressed and has high accuracy.**

Index Terms - Upper limb exoskeleton robot; Rehabilitation training; Flexible transmission

I. INTRODUCTION

Stroke, also known as Cerebrovaseular Accident (CVA), is a group of diseases caused by acute cerebral vascular circulation disorders which has high morbidity and high mortality [1]. According to the data published by Committee for the prevention and treatment of stroke of the National Health and Family Planning Commission. Currently, There are about 1.5 million new stroke cases in China each year, of which the rate of death or disability is higher than 75%. Besides, 85% of survivor is suffered from varying degrees of heminlegia because of the damage of motor nerve [2]. So the rehabilitation therapy for hemiplegia after stroke has become a focal point of modern rehabilitation medicine and rehabilitation project.

Rehabilitation robots can provide continuous, effective and multimodal rehabilitation training for patients with hemiplegia [3]-[5]. It can strengthen patients' active training consciousness and speed up the recovery process of motor function of affected limb [6]. Besides, we can obtain some data by sensor system attached to the patients in the process. In this method, it combines neurophysiology, biomechanics, sports science and behavioral science, which emphasize the importance of subjective participation and cognition in patients.

As the first one of famous upper limb rehabilitation robot, MIT-MANUS was designed by Hermano in [7]. They built a wrist module for robotic therapy to meet particular patient needs. In [8], Patricia Kan designed and developed the POMDP system in the University of Toronto. The robot device had two degrees of freedom (DOFs), which allowed the reaching exercise to be performed in 2D space. In [9]-[10], The Stimulation Assistance through Iterative Learning(SAIL) platform was implemented by Z.Cai in the University of Southampton in 2011. SAIL system combines functional electrical stimulation (FES) with mechanical arm support, to assist patients performing 3D reaching tasks in a virtual reality environment. Within a few trials, results showed that training with SAIL can augment patients' remaining movement. In [11], a stroke rehabilitation robot for upper extremity called RUPERT was designed by Hang Zhang in 2011. Different with robots mentioned above, RUPERT made enjoyable effect in statistical tests due to applied of pneumatic muscle which can turned on to drive each DOF to follow the planned trajectory.

Meanwhile, the application of rehabilitation robot system in China is also introduced in papers. In 2009, a five DOFs upper limb rehabilitation robot system based on sEMG control was developed in Harbin Institute of Technology [12]-[13]. In [14], a nine DOFs exoskeleton rehabilitation robot driven with pneumatic muscles was designed in Huazhong University of Science and Technology. A renewed second generation exoskeleton upper limb rehabilitation robot was presented in the Shanghai Jiao Tong University in [15]. Furthermore, a package of VR game training software and VR kinematics evaluation software was programmed in [16], which developed an evaluation method based on sEMG.

The majority of upper limb rehabilitation exoskeleton robot have some problems, such as complex structure, single mode of motion, much fixation without flexibility, heavy weight to give patients extra burden, lack of safety protection device.

In this paper, we developed a design of upper limb exoskeleton rehabilitation robot with 3 DOFs. In the normal activities of the human body, the elbow can complete one degree of freedom of movement, the wrist can complete two degrees of freedom movement. The robot can complete these three motions above. In addition, the joints of the robot are mostly in adjustable size, which expands the population of applicable patient, making the patients comfortable to wear. Besides, this robot can improve the disadvantages mentioned above.

This paper is organized as follows. In section I, some research present situation in the domestic and foreign about upper limb rehabilitation robots are introduced first. Then the device which mainly consists of 3-DOFs of rehabilitation system will be presented respectively in section II. The experiments are carried out for the error in the movement of elbow joint and discussed in section III. The last section presents some conclusions.

II. Analysis and Design of Device

A. *The Requirement of the Design*

Three key requirements taken into consideration during the conceptual design stage of upper limb rehabilitation exoskeleton are,

1. Be flexible to wear, light weight, high accuracy in movement for patients.
2. Ability to apply enough power for combinatorial actions of the patients.
3. The movement space must be in accordance with human physiological structure.

For patients with hemiplegia caused by stroke, rehabilitation device should achieve the function that the human body can flexibly perform a set of different actions. It must be easy to wear, especially for the disabled. Our target is to make it convenient for patient to do the training at anywhere by himself.

Giving the purpose of our design, the device should provide enough power to perform the passive movement for the patients. The actuator should be high capacity to drive both the device and the upper limb to move. The material of the device should have high strength to forbid the poor performance of device in the movement.

For most patients, there are many sizes of length or width of upper limb which should be seriously considered. So the adjustable design is much more better though the difficulty will exist when we conduct the idea of both flexible to wear and adjustable to most patients.

Besides, the combinational movement is much more better for the rehabilitation process of patients [17]. Our device should conduct the combinational movement freely and with no interference.

This design combines 3-degree-of-freedom where one for elbow joint and two for the wrist. The elbow joint of the human body has only one DOF, flexion and extension. And the wrist has three DOFs, which we just design for two DOFs, namely flexion and extension, pronation and supination. The range of each motion is shown in the following table I .

TABLE I
Range of Three Degrees of Freedom

3-DOF of Joint	Elbow Joint	Wrist Joint	
	Flexion/ Extension	Flexion/ Extension	Pronation/ Supination
Limit Angle	-60°~180°	-60°~60°	-90°~90°
Motion Range	-45°~180°	-60°~45°	-60°~90°

B. *Description of 3 DOFs Exoskeleton Mechanical System*

The robot is designed as a portable and training device. In fig.1, it consists of three parts: flexion and extension of elbow, rotation of wrist, flexion and extension of wrist. Each part corresponds to a degree of freedom, which is performed by different structures. These three components works together to complete a process of training and detecting the movement.

The transmission part uses wrapping connector driving, composed of a line pipe and wire rope, which is conducive to free the motor from the device. This design reduces the burden on the hands of patients and make the design more flexible. The weight of the whole device is 3.34kg, which is lighter than the design of existed device [18]. However, the wrapping connector driving will inevitably bring the error in the accuracy of the transmission. The error of accuracy will be discussed in the experiment of next section.

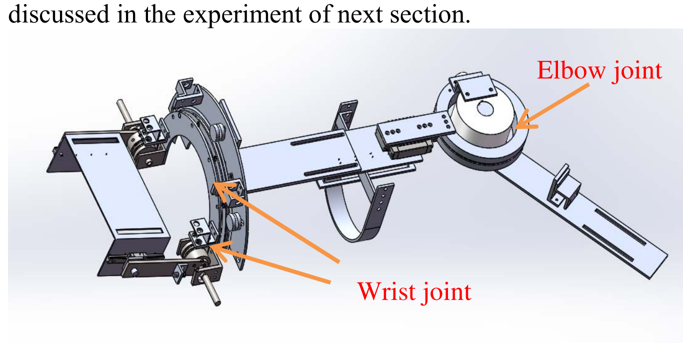


Fig.1 The structure of the device

C. *Flexion and Extension of Elbow*

This part aims to complete the movement of the elbow's DOF in fig.2. The utility model is composed of the fixation part, a connecting plate and the rotating shaft. The fixation plates, one attached to the upper arm and the other attached to the forearm, fasten the device in upper limb. The square groove of the fixation plates are used to fasten the bandage on patients. The rotation of the rotating shaft drives the movement of the forearm when the torque is provided by the transmission part. The application of the slide rail and the adjustability of the connecting rod allow the device to be suit for more people. In the middle part of the joint, a rotary encoder is added to detect the position of the device in real time, which give patent the reliable security guarantees.

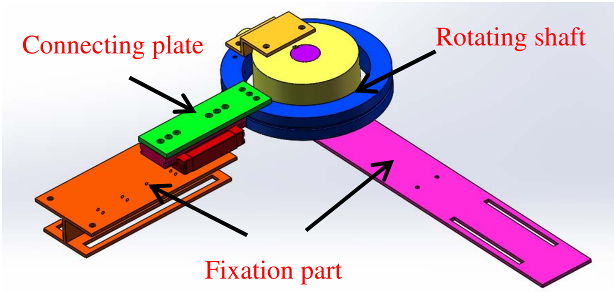


Fig.2 Flexion and extension of elbow

D. *Rotation of Wrist*

In fig.3, this section is mainly divided into fixation part and rotating part. Compared to the design of elbow joint above, it is added a caging part, which can limit the range of this rotation to -10°~80°, compared to -90°~90°(the range of human's wrist). The rotating part is limited by four pairs of ball bearings. The wire rope is wound around the rotating part (not shown in the picture). The rotating part is fixedly attached to the palm portion of the human body. In the duration of movement, the torque is transmitted through the transmission, driving the rotating part to rotate, and then driving the rotation of the palm. By the limiting part, this DOF can only be moved at a given angle in the particular position, which ensures the safety and stability of the training.

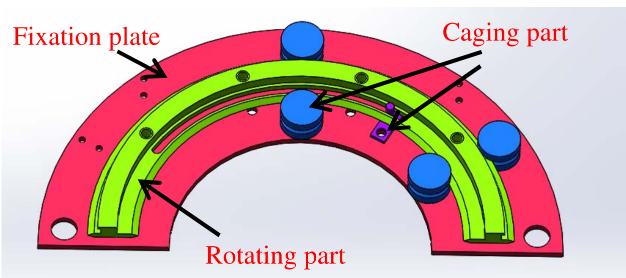


Fig.3 rotation of wrist

E. *Flexion and Extension of Wrist*

In fig.4, this section is also made up of three parts, the rotating part, the fixation part and the caging part. In this DOF, there is also a finite position device that limits the rotation angle by changing the shape of the fixation position. The design of the limiting device limits the degree of rotation's movement to the angle of 0°~90°. It is arranged in the wrist joint, where the rotating shaft should be coincided with the rotating shaft of the wrist joint. By using the force of the rotating shaft, the wrist movement is driven.

The device uses a flexible transmission to be driven. The wrapping connector driving is composed with a hose sleeve and wire in fig.3(a), which can extend the action point of the force to facilitate the placement of the motor, and it will effectively reduce the additional burden on the patient. But the wrapping connector driving may bring the error on accuracy which makes the experiment on the accuracy of the device essential.

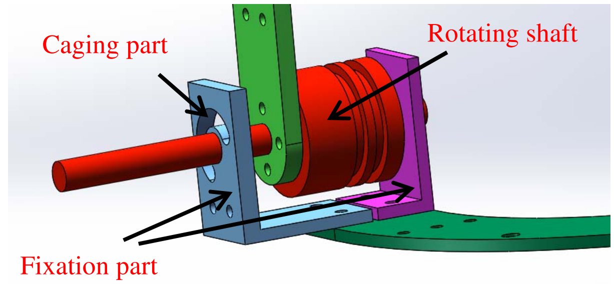


Fig.4 Flexion and extension of wrist

III. SYSTEM EVALUATION

Because of the flexible transmission, the actual accuracy of robot's operation can not be guaranteed and it is necessary to design experiments to verify and analyse the experimental error. This experiment is designed to get the data of motor and rotary encoder in fig.6(b), analyse the difference between by using software, and finally evaluate the device according to the result. During the movement of the elbow, we obtain the data of motor and rotary encoder as the actual difference between the input and the result. By analysis of the difference, we can get the conclusion of the final accuracy rate. The source of this error comes from the process of driving mode where the wire rope produces a thread error in process of tension and loosen in fig.6(c).

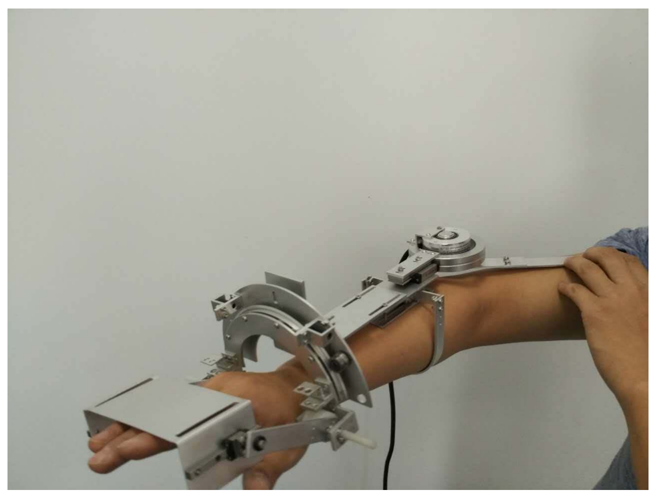
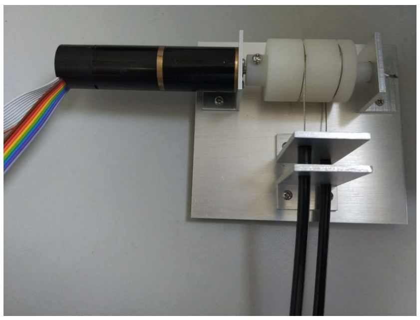


Fig.5 System evaluation

In the experimental setting, the relationship between the palstance of the motor and the rotary encoder should mainly be analyzed. The accuracy of the flexible transmission is illustrated by calculating the errors between them. Both the motor and the rotary encoder are connected to the PMAC, and the experimenter wears the device. The motion of the elbow joint was experimentally tested ten times. We make it constant that the motor rotates at a speed of 3 rad/s, while the steel rope drives the movement of the elbow joint. The upper arm is perpendicular to the ground, and the forearm moves under the force of the device. In the experiment, the numerical values of the motor and the rotary encoder are analyzed [19].

(a) Flexible pipe and wire rope

(b) Rotary encoder



(c) Motor and fixation parts

Fig.6 Experiment of elbow's movement

The motor has 2000 pulses per second. It has a high degree of accuracy. The input data of motor and rotary encoder refers the displace that can not judge its accuracy intuitively. So we take the palstance value as estimation, the palstance value is as follows:

$$\omega_i = (\theta_{i+1} - \theta_i)/\Delta t \qquad (1)$$

In Eq.(1), ω_i approximately refers to the palstance at that moment; θ_{i+1} and θ_i respectively refer to the angle of last moment and this moment. Δt refers to the time interval between θ_{i+1} and θ_i. In this experiment, we compare the palstance to evaluate the error since the angle is not appropriate variable because of instantaneity and intuition. By using the palstance we can intuitively find out the difference of motor's and rotary encoder's motion state on the basic of time and amplitude.

From the collation of data above, we can get the result of the motor and of the rotary encoder in fig.7. The first chart is about the palstance of motor where the data is gradually smooth to a number less than 3 rad/s. We tend to attribute this error to the resistance of the device. In the second chart, it's about the palstance of rotary encoder. We can see the lag phenomenon in initial 170ms where the palstance is continually stay static. Between 170ms and 200ms, the curve of this chart has a short time of fluctuate which can be explained as the normal phenomenon when the wirerope is being tensioning. After 200ms, the wirerope is tensioned and the rotary encoder smoothly rotates in company with the rotates of elbow device. In this moment, the palstance of rotary encoder is equal to the palstance of motor. The third chart is the deviation of palstance between the motor and the rotary encoder. The result is obtained by calculating the difference of these two data. It shows the difference of two in 500ms.

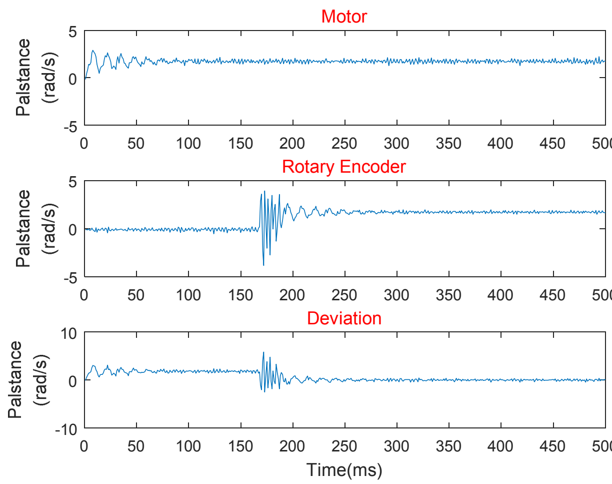


Fig.7 The data of motor and rotary encoder

After the deviation is obtained, we want to evaluate this error. By the Eq.(2), we can get a chart of error rate in fig.8.

$$\gamma_i = \frac{\omega_i - \phi_i}{\phi_i} \times 100\% \qquad (2)$$

In Eq.(2), γ_i refers to the error rate at each moment; ω_i and ϕ_i represent the palstance of rotation measured by the motor and the rotary encoder. In fig.8, it shows the diversification of the error rate in 250ms. We can intuitively deduce that the palstance of these two parts have difference in the whole movement. But it is a regular process and the positive value and negative value could be offset. However it is just a deduction. To prove the deduction, we integrate the difference and get the final error which is less than 8.3%. Compared with the existed experiment result (the average error rate is less than 9.5%) [20]. This device make an improvement in error rate though the flexible transmission will easily have larger error rate.

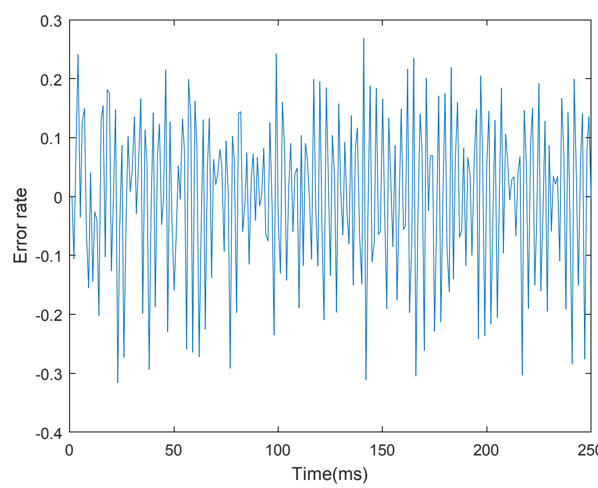


Fig.8 The error rate of palstance

In the real situation, the displacement of motor and rotary encoder have small error when the palstance is approximately equal. To show the error more clearly during the movement, we choose the palstance as the index to show the difference of these two parts, and take the integration of the palstance deviation as the index to evaluate the error of the device.

The main factor of error is the tightness of the wire rope. In this experiment, we measure the motion data of the motor and the device. The initial data is about displacement which can not be compared directly. So we use differential subtraction in Eq.(1) to get the palstance of these two measurement. The comparation of two data is performed in fig.7 where the deviation is also calculated and expressed. In fig.7, we can obviously find the delay between these two data which is about 180ms. We attribute this delay to the process that wire rope changes from loosen to tight. In this period, the rotary encoder is stationary while the motor starts running at the speed of 3rad/s. After the delay, the motor and rotary encoder is rotating synchronously with same palstance with some error. Then we do manipulation data in Eq.(2) to get the error rate in unit time and drew a chart in fig.8. It is used to make the error more intuitive. To get the final error rate of this DOF, we integrate the deviation in fig.7. And the final error rate is 8.3% where the accuracy rate is 91.7%. For this experiment we made a total of ten trials and this accuracy rate is a final average error rate.

IV. CONCLUSION

The robot assisted rehabilitation training for hemiplegia patients is a new research hotspot where more and more people pay attention to it. In this paper, the main structure of robot is described detailedly. This paper analyzes the motion forms of three degrees of freedom on the upper limb, and designs the device from the view of ergonomics. Because of the application of flexible transmission, the experiments and data analysis about accuracy rate is carried out and come to the conclusion that the robot has the acceptable accuracy rate in its movement. The utility model can overcome the disadvantages of the prior mechanical device, such as large weight, insufficient accuracy, non-portable. In addition, by using flexible mechanical design, it can greatly reduce the weight of the device, lighten the burden on patients. The experiment and the analysis of the data shows that the robot has good performance in movement. Overall, the device achieved the desired purpose that it can help patients complete rehabilitation training and achieve a certain degree of rehabilitation. Moreover, it has the advantages that the previous product does not have and may be applied to the wider population.

ACKNOWLEDGMENT

This research is partly supported by the National High Tech. Research and Development Program of China (No.2015AA043202), and National Natural Science Foundation of China (61375094, 61503028).

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