

Design of the Structural Optimization for the Upper Limb Rehabilitation Robot

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Abstract -The exoskeleton robotic rehabilitation training system is a branch of the field of robotics, it is the external mechanical system that is consistent with the similar joints of the human body, and attached to the human body. With the development of exoskeleton rehabilitation robotic system, the biomechanics influence of device should be considered in rehabilitation training. This paper proposes a novel upper limb exoskeleton rehabilitation device based on biomechanics, which can be used in rehabilitation of upper limb for hemi paralysis patients. This system aims at helping hemi paralysis patients recover motor function of upper limb; in addition it is suitable for variety of patients. This system is portable and wearable, which consists of exoskeleton device, hepatic device (PHANTOM Premium), motor controllers and work station (computer). This paper proposes a structural optimization scheme in order to solve some problems of bowl's structure of the rehabilitation robot. The Pro/ENGINEER Wildfire (Pro/E) software is applied to get a three-dimensional modelling, kinematics simulation and dynamic analysis of the rehabilitation robot. From the analysis, the robot end motion simulation curves were obtained to verify the optimization structure reasonable and better motion characteristics. In the future, this structure will have a wide application prospect in the rehabilitation therapy field.

Index Terms- *Upper limbs rehabilitation robot; Structure optimization; Kinematics simulation; Exoskeleton robotic system*

I. INTRODUCTION

The upper limb rehabilitation robot is mainly suitable for the stroke patients caused by skeletal muscle function, loss or decline, and central nervous system damage, unable to form the effective control of limb movement in patients with stroke. The stroke is often called the "stroke or cerebrovascular accident, refers to the brain caused by persistent neurological deficits acute cerebral vascular disease, the prevalence of 85% cause hemiplegic symptoms [1], especially in the elderly. According to statistics, the annual China stroke about 1 million 500 thousand new cases of stroke patients, the national about 8million, disability rate is as high as 75%. According to the global distribution of stroke mortality, China annual stroke mortality about 151 ~ 251 / 100 thousand [2]. Results of China residents of the third death sampling survey published in 2008 showed that: stroke has become the first cause of death in the world. Health Organization Monica research data show that: Chinese stroke rates higher than the global average, the United

States is more than 2 times, and at an annual rate of 8.7% rise. Therefore, the upper limb rehabilitation training is particularly important in the domestic research institutions [3]. At present, most of the countries of the exoskeleton robot are in the basis of the initial stage. However, United States and Japan, France, Russia, Korea is in advanced level for the exoskeleton robot technology achievement. While the research on the field of exoskeleton rehabilitation robot is relatively late in our country [5], but with the exoskeleton robot in the society's increasing demand, the natural science foundation of China's national science and technology support program 863, and also gradually to carry out the corresponding research [6].

The upper limb rehabilitation robot can be divided into two categories, one is the end traction rehabilitation robot system, and another one is for exoskeleton rehabilitation robot system. In the domestic and foreign research, the representative has: In the domestic and foreign research, the representative robots is following: MIME robot, developed by Stanford University, combines the advantages of the endpoint and the external skeleton, which can be used to control the force moment in different parts of the patient's body [7]. The patient is going to wear an exoskeleton device which can provide both the resistance and assistance to the affected arm [17]. California University and University of Chicago joint research and development of Guide ARM upper limb rehabilitation device, the upper arm and elbow joint internal rotation / external rotation movement using the external skeletal structure, while the shoulder movement is driven by the end of the arm connected to the upper arm and fixed on the wall. EMG signals are used as input in the proposed method for the elbow ad wrist joint [16] [18] [19].With the increasing number of universities and other research institutes to join [8], the development of the robot technology of rehabilitation robot, such as the British University of Southampton study of the 5-DOF robot arm SAIL, the robot is not driven, in the two shoulder, elbow rotation of the joint with a torsion spring support system. RUPERT mechanical arm developed by University of Arizona, for the first time using the artificial pneumatic muscle [9] [10], achieving the shoulder flexion / extension movement, elbow flexion / extension, forearm rotation, wrist / swing, so that the manipulator has a better flexibility, but also to make the robot more portable. A 7-DOF mechanical device CADEN-7 was developed by University of Washington, seen as a novel driving mode, most of the drive

and gear reducer are put in the shoulder, which can realize the long-distance transmission [11]. The robot has simple structure, light and convenient, but it is easy to occur elastic sliding to make the robot movement is not accurate [12].

With the improvement of people's living standard, in order to make the robot is more portable, some patients put forward a personal request to the robot, and the robot will meet people's needs.

II. STRUCTURE OF REHABILITATION SYSTEM

The aim of the upper limb rehabilitation device is designed to restore the movement function of the upper limb. This paper introduces the robot that main helps patients achieve includes elbow, wrist joint movement. The three degrees of freedom motion, including elbow bending and stretching [13], the wrist bending and stretching and wrist rotation are designed for the robot. Meanwhile the three-dimensional position information of the patient and the force information of the robot arm were feedback to the control system through the force sensor on the exoskeleton rehabilitation. Exoskeleton material for aluminium alloy, light in weight, total weight of 1.3 kg, tensile strength, extension, and its design human engineering, so very comfortable and convenient to wear can be portable to carry [14].

The exoskeleton device is fixed on the paralysation upper limb. With the uninjured upper limb, patients change the PHANTOM Premium state to control the exoskeleton device to implement rehabilitation training (Fig.1, Fig.2) [20]-[22].

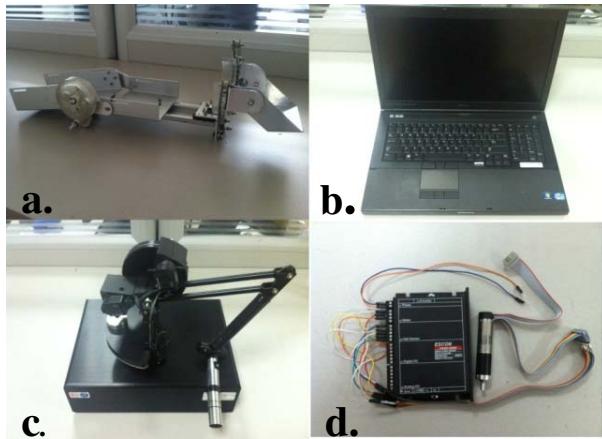


Fig. 1 Structure of rehabilitation system: (a) exoskeleton device; (b) work station; (c) phantom; (d) motor and controller.



Fig.2 Wearable Demonstration of Exoskeleton Device.

Meanwhile, therapist can obtain the motion information of upper limbs of patients by using inertia sensor, including Position, Velocity and Acceleration. The force sensor is used to keep safety and obtain the force information in the training. By this information, therapists set up better training method for patients [15].

III. DESIGN AND OPTIMIZATION OF THE ROBOT STRUCTURE

A. Bowl's Structure

Original robot wrist transmission system is driven by a wire rope, the driving system of wrist stretch flexion and extension mainly consists of a driving motor, wire rope and with the steel wire rope from the wheel composition shown in figure. 3. Control wrist rotation of the driving system mainly consisted by the motor, wire rope, driven ring, annular slide rail and the slide bearings.

B. Defects of Structure

Wire rope drive is a kind of under actuated mode and it has advantages such as light weight, low impact, low friction, while the most important advantage of the drive mode is that high load transmission can be realized in a long range. However, the small size of portable rehabilitation robot work space is the limit; in this case the rope drive mode not only doesn't play the advantages of rope drive, but cause the loss of

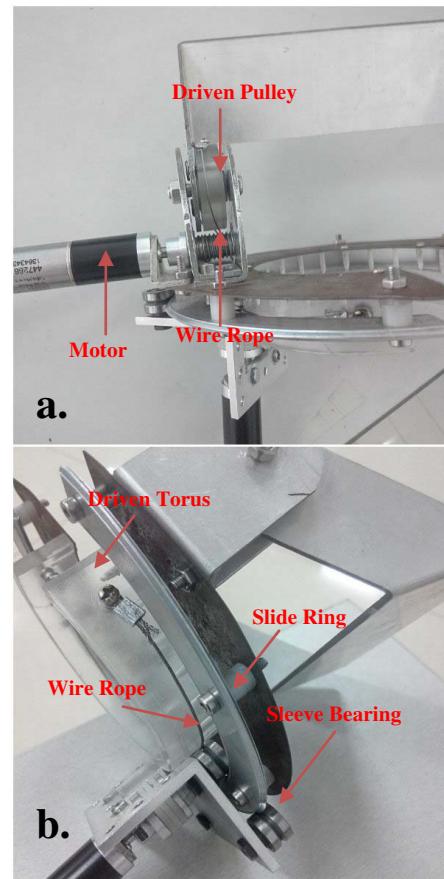


Fig. 3 (a) drivemechanism of wrist's flexion/extension motions;
(b) drive mechanism of wrist's pronation/supination motions.

energy and movement distortion and the inconvenience because transmission ratio is not constant and rope drive can't be compressed but only be pulled. What's worse, slide type annular slide way can cause the high friction transfer movement and easy to deformation. As a result, the energy will be lost and motion distortion is also a case, meanwhile due to the small motor power, in the control of motor movement will cause more time delay and even motion failure and other serious problems.

C. Optimizational Structure

Based on the above problems we need to the optimization design of the structure of the wrist. After optimizing, gear transmission is adopted for the wrist structure. Gear transmission has many advantages, such as, drive ratio is constant, work smoothly; strong bearing capacity, high transmission efficiency; structure is simple, convenient disassembly and assembly, compact installation, maintenance is convenient and so on.

Bowl's pronation and supination, flexion extension motion of bowl will directly become the load for rehabilitation robot system, so the structure should be as a compact, lightweight design. Motion of pronation external rotation mechanism in the design of a transmission ratio to meet the small power motor drive. Through a pair of transmission ratio of 1: 4 gear drives to achieve its intended action, the big gear structure is shown in figure 4. Big gear and a handle connected to the gear rotates to drive the front arm to rotate, so as to realize the

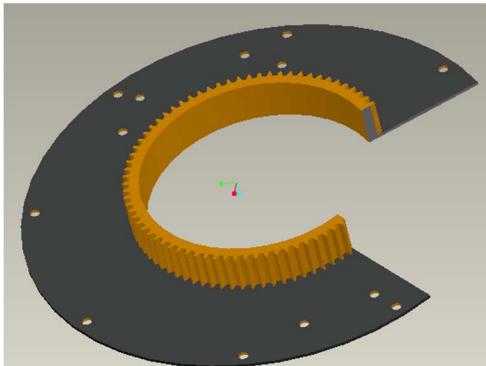


Fig.4 Optimized large gear structure.

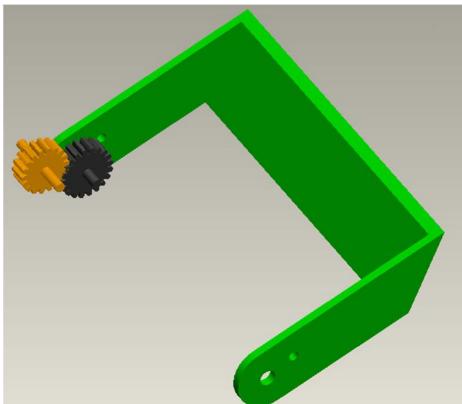


Fig.5 Optimization structure of flexion and extension of bowl.

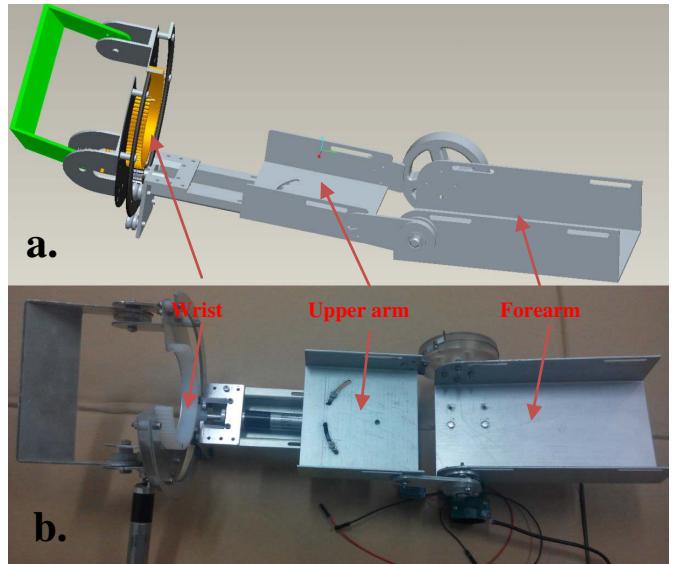


Fig.6. (a) the three-dimensional modelling of the robot and (b) the real robot structure.

whole arm along the upper longitudinal axis. The bowl of flexion extension motion gear as shown in figure 5, the passive gear and a handle connected to implement the bowl of flexion and extension movement.

According to the above requirements as well as structural analysis and optimization of the structure of three-dimensional structure is shown in figure 6.

IV. KINEMATIC ANALYSIS OF OPTIMAL STRUCTURE

This paper introduces the rehabilitation robot structure optimization is completed by software Pro/E. With Pro/E for design optimization of the structure of drawing and parts assembly, final reoccupy Pro/E motion simulation function and mechanism motion analysis function for motion simulation and kinematic analysis. Pro/E is a 3D modelling and Simulation of mechanical motion, as a new standard in the field of mechanical CAD/CAE/CAM in today world, for the recognition and promotion of the industry, Pro/E is one of the mainstream CAD/CAE/CAM software, especially in the field of domestic (Chain) product design occupies an important position.

A. Mathematical Modeling of the robot

The Jacobian matrix plays a very important role in robot kinematics, dynamics and manipulator control. Jacobian matrix is a transfer matrix, it will joint space of joint variables passed to Cartesian space and make the robot end effector produce differential movement, offering the rod actuators with operating speed and rod speed, especially the end effector is synthesized in the speed between the relationship, so Jacobian matrix is seen as from the joint space to the operating space velocity of transmission ratio [4].

Motion equation of the robot

$$\mathbf{X} = \mathbf{X}(q) \quad (1)$$

Where, \mathbf{X} represent the operation space and q represent the

joint space between the displacement relationships. On both sides of the derivative of the time t , we can acquire that the differential relationship between $\dot{\mathbf{q}}$ and $\dot{\mathbf{X}}$

$$\dot{\mathbf{X}} = \mathbf{J}(\mathbf{q}) \dot{\mathbf{q}} \quad (2)$$

Where, $\dot{\mathbf{X}}$ is the speed in the operation space of generalized velocity, referred to as the operating speed; $\dot{\mathbf{q}}$ is the speed for joint velocity; $\mathbf{J}(\mathbf{q})$ is partial derivative matrix of $6 \times n$, called the Jacobian matrix of the robot.

For a given $\mathbf{q} \in \mathbb{R}^n$, Jacobi $\mathbf{J}(\mathbf{q})$ is a linear transformation from the speed of the joint space to the speed of the operation space.

$$\mathbf{D} = \mathbf{J}(\mathbf{q}) \mathbf{d}\mathbf{q} \quad (3)$$

$$\mathbf{V} = \dot{\mathbf{X}} = \mathbf{J}(\mathbf{q}) \dot{\mathbf{q}} \quad (4)$$

\mathbf{D} is the differential motion vector of coordinate system, formed by differential motion vector \mathbf{d} and differential rotation vector \mathbf{s} , which is 6 dimensional column vector, $\mathbf{D} = \begin{bmatrix} \mathbf{d} \\ \mathbf{s} \end{bmatrix}$.

\mathbf{V} is generalized velocity of coordinate system, constituted by linear velocity vector \mathbf{v} and angular velocity $\boldsymbol{\omega}$, is 6 dimensional column vector,

$$\mathbf{V} = \begin{bmatrix} \mathbf{v} \\ \boldsymbol{\omega} \end{bmatrix} = \begin{bmatrix} v_x & v_y & v_z & \omega_x & \omega_y & \omega_z \end{bmatrix}^T \quad (5)$$

Portable upper limb rehabilitation robot for this article, the 3 joints are all rotary joints, so Jacobi matrix $\mathbf{J}(\mathbf{q})$ is a 6×3 order matrix. Among them, the first 3 lines represent the transmission ratio of the arm line speed v , and the later 3 lines represent the transmission ratio of the arm's angular velocity $\boldsymbol{\omega}$. On the other hand, each column of the matrix represents the corresponding joint velocity \dot{q}_i ($i=1,2,3$) which corresponds to the transmission ratio of the linear velocity and angular velocity of the hand. Therefore, the Jacobi matrix $\mathbf{J}(\mathbf{q})$ block can be used[16].

$$[\mathbf{v}] = \begin{bmatrix} J_{l1} & J_{l2} & J_{l3} \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{bmatrix} \quad (6)$$

Then, the arm line velocity v and angular velocity $\boldsymbol{\omega}$ can be expressed as q_i linear velocity of each joint function,

$$\begin{cases} v = J_{l1}\dot{q}_1 + J_{l2}\dot{q}_2 + J_{l3}\dot{q}_3 \\ \boldsymbol{\omega} = J_{a1}\dot{q}_1 + J_{a2}\dot{q}_2 + J_{a3}\dot{q}_3 \end{cases} \quad (7)$$

J_{li} and J_{ai} is the joint i unit of joint speed caused by the line speed and angular velocity of the arm, respectively.

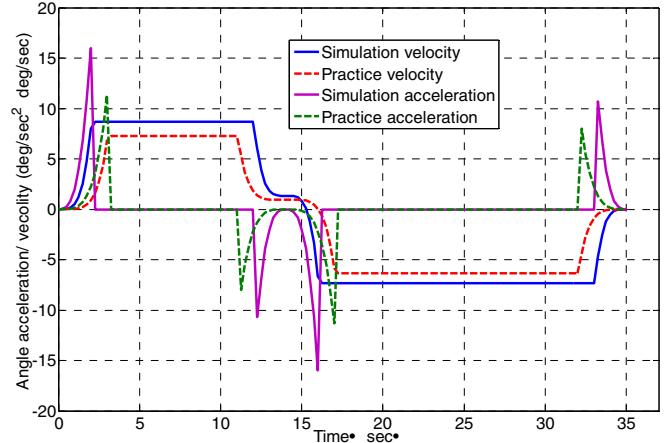


Fig.7 Angular velocity and acceleration curve for the simulation and the actual movement of the wrist movement (Flexion/Extension).

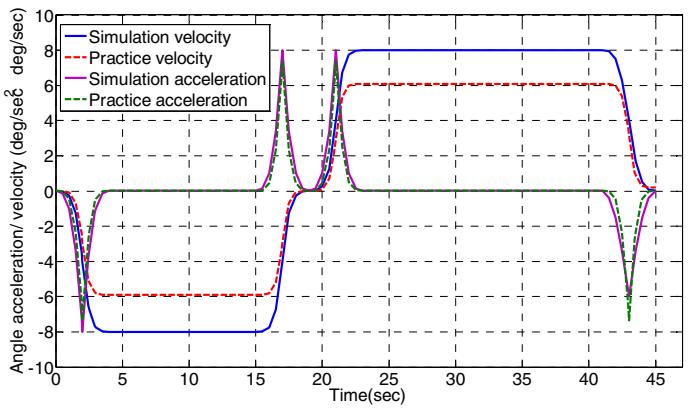


Fig.8 Angular velocity and acceleration curve for the simulation and the actual movement of the wrist movement (Internal /External rotation).

B. Kinematic Analysis

The two degrees of freedom of the bowl are driven by a small power DC motor, and the angle velocity and the angular acceleration of the end reference point obtained from the motion of the flexion and extension of the bowl and the experiment are shown in figure 7. Will, the curve of the wrist motion simulation and experiment of the internal and external rotation is shown in fig 8.

In the figure we can see, in order to make the patients, when trained, not be caused two damage because of the robot's irregular movement at trainers controlling the motor, the speed of the motor is controlled at law of motion is: zero - acceleration - constant speed - reverse acceleration - constant speed - deceleration - zero. It can be seen from the figure that the simulation curve and the actual movement curve are basically the same. However, due to the existence of the system, there are some other factors, such as the friction force and the weight of the robot itself, which lead to a certain deviation between the simulation curve and the actual curve. In Figure 8, due to the inertia of the motor and the control of the delay, resulting in simulation acceleration and the actual acceleration is not synchronized. Fortunately, these errors are in the acceptable range, which proves the success and the desirability of the structure optimization.

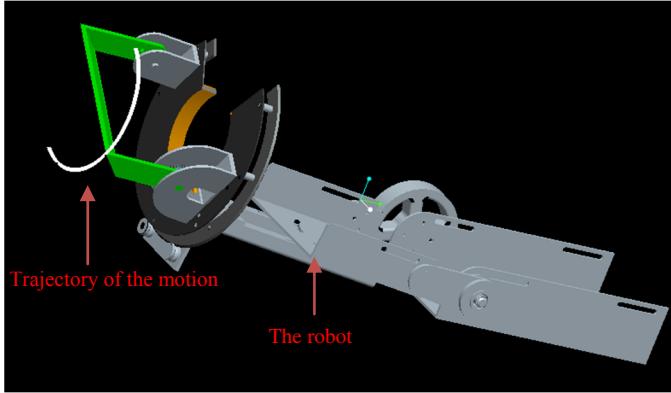


Fig.9 Trajectory of internal /external rotation motion.

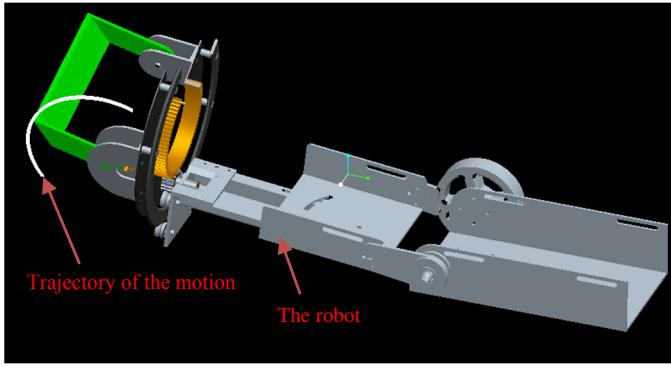


Fig .10 Trajectory of flexion/extension motion.

Figure 9 and 10 is comparison curve of the wrist with two degrees of freedom motion angle range between before and after optimization structure.

C. Contrast before and after optimization

The design of the robot upper limb three degrees of freedom movement of the human body schematic diagram is shown in the fig 11.

The range of motion of the robot's degrees of freedom and the range of motion before and after the optimization are shown in the following table I.

In Figure 12 and figure 13 we can see that the optimization of the structure of the movement is greatly increased, which will give different degrees of rehabilitation patients with targeted rehabilitation training. Better structure rehabilitation effect after optimization and the bed boom is more stable.

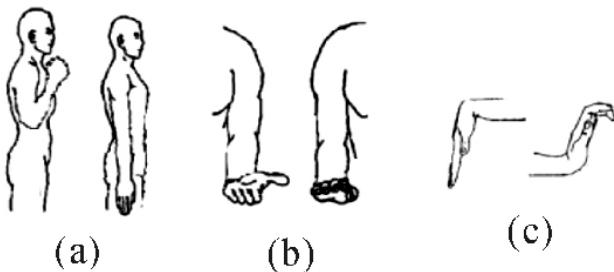


Fig 11. Schematic diagram of human upper limb movement

Table 1 : Angle and design of joint movement of human body

Sport name	Body Degree	Before optimization	After optimization
Flexion/Extension (a)	$0 \sim 140^\circ$	$0^\circ \sim 130^\circ$	$0^\circ \sim 130^\circ$
Internal /External (b)	$-90^\circ \sim 90^\circ$	$-60^\circ \sim 60^\circ$	$-90^\circ \sim 90^\circ$
Flexion/ Extension (c)	$-60^\circ \sim 90^\circ$	$-45^\circ \sim 70^\circ$	$-60^\circ \sim 90^\circ$

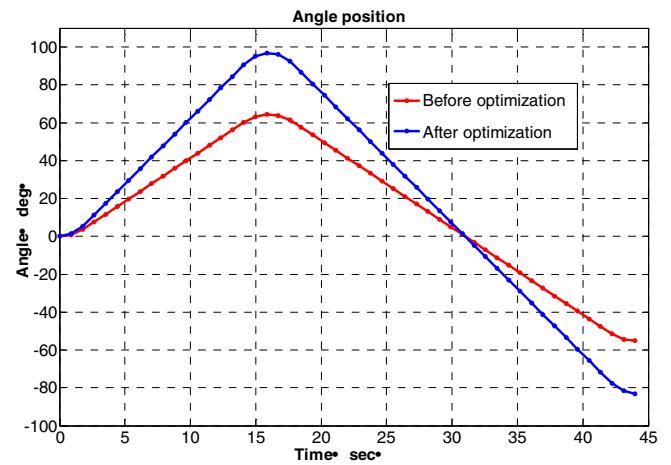


Fig .12 Comparison curve for angular range between internal and external rotation.

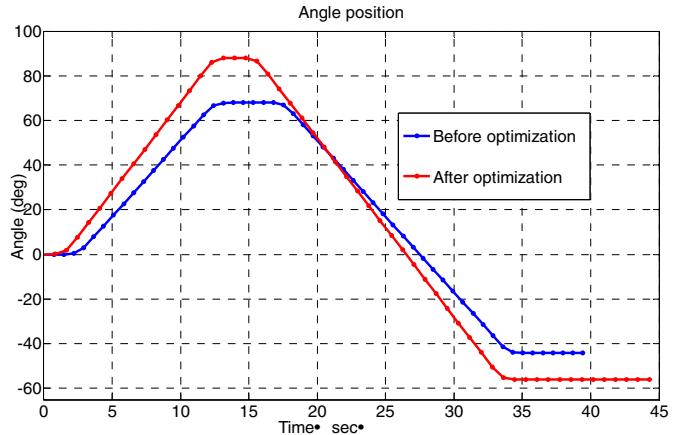


Fig .13 Comparison curve for angular range between flexion and extension motion.

We can clearly see that the optimized structure of the range of motion increased significantly, proving once again that the optimized structure is more suitable for rehabilitation training of patients, can according to different degree of stroke patients, and more convenient and reliable.

Another degree of freedom is not described in this paper, and its analysis of motion will be shown to you in the future work [10].

V. Conclusion

In this paper, the design of optimizational structure for the external skeletal upper limb rehabilitation robot is proposed to assist the stroke patients to recovery the motion function,

according with the physiological structure of the human body. We get the robot motion simulation by using Pro/E simulation software. From the experiment of the simulation, the robot has the advantages of rehabilitation, and has a smooth motion. The improved structure has a larger range of motion and stronger adaptability. What's more, the motion simulation and kinematics analysis are achieved to prove the feasibility and reliability of the structure movement. In addition, the rehabilitation robot can be used by patients, not only in the hospitals for rehabilitation, but also be used when patients are not in hospitals, which bring great convenience for hemiplegic patients.

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