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Radial Basis Function Neural Network-based Control Method for a Upper Limb Rehabilitation Robot

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Abstract **-As the third disease of death and disability in the world, stroke makes a huge difficulty to patients for activities of daily living. Upper limb damage after stroke is caused by weakness, joint out of control, paralysis and abnormality. With the increasing number of patients with hemiplegia, the technology of rehabilitation robots has also developed rapidly. At the same time, the control system of the robot is continuously improved. The conventional PID control system presents many drawbacks. The biggest safety hazard through experiment testing is that the system is out of control, in order to better ensure the safety of patients. In this paper, the ANSYS finite element analysis is used to analyze the mechanical structure of the mechanical structure, and the RBF neural network control system is introduced to improve the control strategy of the upper limb rehabilitation robot, which makes up for the shortcomings and safety hazards of the conventional control system. Through the results of MATLAB simulation, the control effect of the control system is evaluated to ensure its safety and stability, so that more patients with hemiplegia can reduce the pain and get safe and effective treatment.**

Index Terms: Radial Basis Function (RBF) Neural Network. Rehabilitation Robot. ANSYS Finite Element Analysis. MATLAB Simulation

I. INTRODUCTION

Stroke is one leading cause of movement disability in the US and Europe. There are also a large number of patients with deaf in China, which not only bring pressure and trouble to the family, but also exert great pressure on the society. By 2030, it has been estimated that there could be as many as 70 million stroke survivors around the world [1]. Since the end of the nineties, there has been a burst of research on and development of robotic devices for rehabilitation, particularly for the nerve rehabilitation of post-stroke patients [2], [3]. Robotics is a possible solution to supply magnitude, by providing the number of repetitions which a therapist could impose, as well as motivation thanks to technology appeal, virtual reality, and gaming [4].

In China, the number of disabled people with upper limb function impairment is huge, and the development of high-end medical services has become a major trend in national medical development. The development of effective rehabilitation robots can not only improve the level of scientific research and technology in the field of rehabilitation technology in China, but also reduce the gap between advanced technologies and developed countries. At the same time, self-owned rehabilitation robots can be widely served in patient groups at low prices. Therefore, the development of advanced equipment for rehabilitation of patients with hemiplegia, especially the upper limb rehabilitation robot, is of great significance for reducing the cost of rehabilitation robots, improving the national science and technology level, relieving the pressure of rehabilitation physicians, and bringing more rehabilitation opportunities to disabled people.

One of the main goals of rehabilitation after nerve injury is to improve muscle strength and motor control as they are part of the patient's functional recovery road map. The list of rehabilitation specialists spends a lot of time providing treatment, with a focus on relieving muscle weakness, motor dysfunction, and abnormal coordination. These treatments are usually performed in a specific task, as there is evidence that there are more treatments that combine the repetitive practices of tasks that are specific to the desired outcome. Effectively improve functional outcomes compared to traditional methods such as neurodevelopmental techniques [5]-[7]. Evidence for task-specific training has a strong basis in both sports learning psychology and neuropsychology. Plasticity associated with using [7], [8]. Some studies have shown that performance improvement is most likely to occur when training is very similar to the specific activities that are expected to improve performance [9]-[11]. The motor activity seen in this type of training is also known to promote neuroplasticity and functional recovery after nerve injury [7]. The two main features of robotic exoskeletons are their ability to exert forces along the auxiliary limbs and provide reliable joint measurements [10]. Although the physical interactions through multiple interaction points have caused people's interest and basic problems from the perspective of control, most of the existing control methods have been developed.

Although there are many comments on robotic exoskeletons, most of them focus on their mechanical properties [12]-[14]. We do believe that the key feature of exoskeletons in neurological rehabilitation is the contrast between them. The strategy above the inherent mechanical behavior of the device (inertia, friction, traceability, etc.) determines the interaction between the human and the robot. A review of high-level control strategies for nerve rehabilitation robots, including operational robots and exoskeleton robots, has existed [15]-[16]. But since these are not specific to exoskeleton, many devices and control methods they are all missing [21], [22].

This study aims to solve the control effect of the challenge to achieve a good control effect of the portable rehabilitation robot. The paper designed a mechanical structure that includes three degrees of freedom bilateral rehabilitation robots. In order to provide patients with a lighter mechanical structure. The paper used ANSYS static analysis to analyze the maximum force and pressure of the mechanical structure, the main role is to select the structural materials and motor specifications. The control system's RBF neural network controller is analyzed by MATLAB simulation software, and the robot is constructed on this basis. Finally, the paper compares the theoretical rotation angle with the actual rotation angle through MATLAB simulation. The effectiveness of this control system is analyzed by comparing the plotted error curve with the set error tolerance.

II. Rehabilitation Exoskeleton System

A. Mechanical structure

The outer structure of the exoskeleton upper limb rehabilitation robot designed in this paper adopts the rigid body structure. The portability light weight and easy operation make the patient only need to wear it on the limb to assist him in performing rehabilitation training. However, during the training, the robot must direct contact with the patient's limb may have a mechanical impact on the affected side of the patient's body. Therefore, an effective and reliable force analysis of the designed rehabilitation robot structure is required to obtain the main support point of the force distribution, so that the drive system is better. Provide power and, more importantly, prevent secondary damage caused to the patient by training by improving mechanical mechanisms and training methods.

The structure of the upper extremity nerve rehabilitation exoskeleton is shown in Fig.1, where (1) is the elbow joint and (2) is the wrist joint. The main purpose of the rehabilitation robot is to meet the multi-joint recovery function. The design structure of this paper can rehabilitate the elbow joint and wrist joint of the upper limb of patients with hemiplegia. The patient can pass the mechanical structure to the three degrees of freedom of the arm during the rehabilitation process. During the healing process, the wearer's hand holds the position in the Fig.1 (3). The arm is fixed using the cloth and the wearing hole at the structure.

B. Electrical control unit

The exoskeleton control system uses closed-loop structure control. In Fig. 2, the electrical equipment uses the EC-max 16 (a), which is from Shanghai Hanhua Company. The motor is the Macson brand ESCON maxon motor (b), and the power supply (c) is the power supply of Beijing Bohui Jiaxing Electronics to supply the controlled equipment.

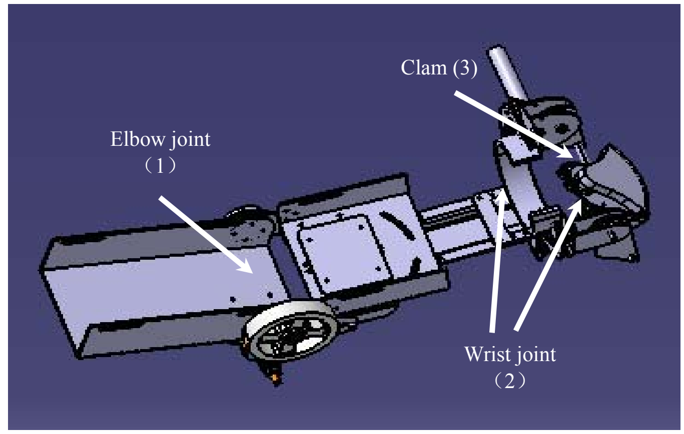


Fig. 1 Main view of the mechanical structure

(a) (b) (c)

Fig. 2 Electrical equipment including

(a) EC-max motor, (b) ESCON, (c)Power Supply

The target control layer is responsible for executing embedded predefined algorithms to control exoskeleton operations. The position of the robot joint is rotated by a potentiometer with a high measurement resolution, avoiding the calibration process.

C. Safety measures

Safety and security are essential for robotic assisted rehabilitation. In the rehabilitation exoskeleton system designed in this paper, the safety and stability of the exoskeleton mechanical equipment and electrical performance are ensured. First of all, to prevent self-collision and exceed the maximum movement, install the mechanical end stop on the drive to ensure that the rotation angle of the exoskeleton is limited to the maximum range of the normal human arm. Secondly, the actual rotation angle of the joint will be out of adjustment. In order to prevent potential harm to the patient, the improvement is to add the corresponding LED light prompt, which greatly reduces the difference of the imbalance phenomenon. Finally, the final safety facility was designed to be the most advanced power-off button, allowing patients and therapists to turn off the motor immediately in the event of a serious system problem. Through the setting of these three safety measures, the maximum limit guarantees the safety of the patient.

III. DEVELOPMENT OF CONTROL SYSTEM

A. Robot system modeling

The design of the mechanical structure is a three-degree-of-freedom upper limb rehabilitation robot, and the robot is composed of a rotating joint (wrist joint) and a telescopic joint (elbow joint). There are also differences in the modeling transfer functions of different joints.

The finite element statics analysis of the mechanical structure of the rehabilitation robot was carried out by ANSYS software. Firstly, the position distribution of the force distribution was analyzed for the elbow joint, and then the force analysis of the wrist joint was performed. According to the color renderings of the simulation results, the force distribution and size of the robot structure are preliminarily judged.

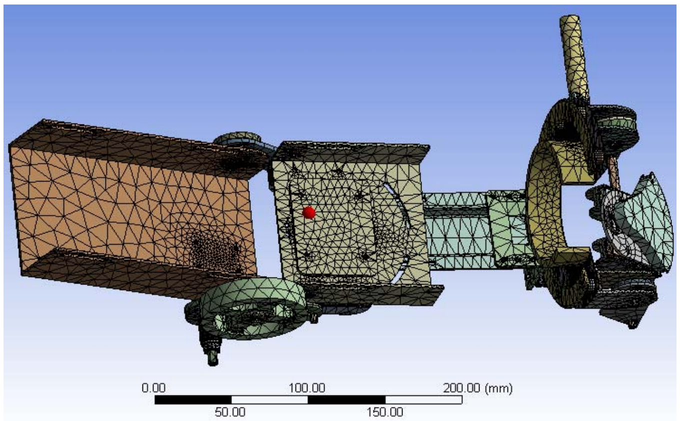


Fig. 3Meshing section

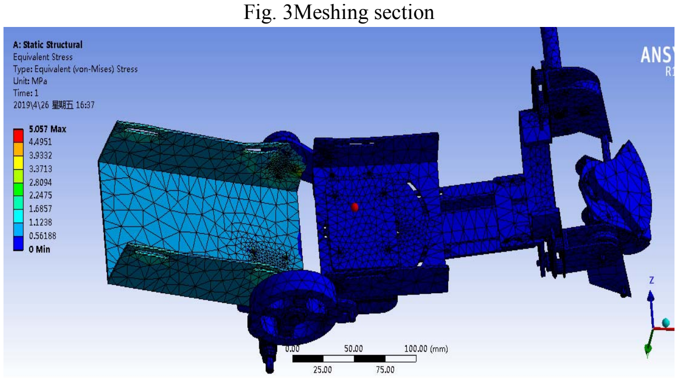


Fig. 4 Elbow joint static structural Equivalent (von-Mises) Stress

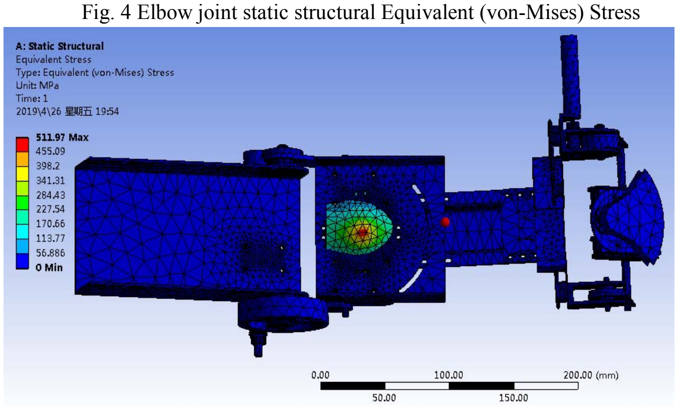


Fig. 5 Elbow joint static structural Equivalent (von-Mises) Stress

B. Control design

The radial basis function network network connection weight has a linear relationship with the output, and the learning process has a fast convergence speed. It has been widely used in nonlinear function approximation and pattern recognition [17]. $X=[x_1,x_2,\cdots,x_n]$ network input. The radial basis vector $H=[h_1,h_2,\cdots,h_m]^T$, the node center vector of the network $C_j=[c_{j1},c_{j2},\cdots c_{jn}]^T$, the network base width vector $B=[b_1,b_2,\cdots b_m]^T$, and the base width parameter all require a number greater than zero, Network weight vector $W=[w_1,w_2,\cdots w_m]^T$ The Gaussian function and the network identification output are as follows [18]:

$$y_m(k)=\omega_1 h_1+\omega_2 h_2+\cdots+\omega_m h_m \tag{1}$$

$$h_j=\exp(-\frac{\left\|X-C_j\right\|^2}{2b_j^2}) \tag{2}$$

The positive definite index of the neural network is:

$$E(k)=\frac{1}{2}error(k)^2 \tag{3}$$

Parameter adjustment of the gradient descent method:

$$\Delta k_p=\eta error(k)\frac{\partial y}{\partial \Delta u}xc(1) \tag{4}$$

$$\Delta k_i=\eta error(k)\frac{\partial y}{\partial \Delta u}xc(2) \tag{5}$$

$$\Delta k_d=\eta error(k)\frac{\partial y}{\partial \Delta u}xc(3) \tag{6}$$

In the formula (4)-(6), the Jacobian matrix of the controlled system is obtained through the identification of the neural network [18].

The rehabilitation training in this paper is realized through human-machine cooperation. The control in the rehabilitation robot includes the control strategy related to people. Therefore, the rehabilitation robot system model containing the patient's active motion intention. Dynamic model of rehabilitation robot:

$$\theta_r(x)x+C_r(x,x)x+K_r(x)+d=f_h+u \tag{7}$$

Among them x, $\dot{x}$, $\ddot{x}$ are the end joint position, velocity, acceleration of rehabilitation robot respective. $\theta_r(x)$ symmetric positive definite inertia matrix, $C_r(x,\dot{x})$ the Coriolis force and centrifugal force matrix of the healing robot, K_r for a rigid array, d for interference, f_h exerting force on the affected limb, u for control input [18]-[20].

The patient's awareness of autonomous movement during training has a crucial role in the rehabilitation process. This paper assumes that the active movement intention of the affected limb can be described as follows:

$$f_h^*=f_h+\theta_h(x)\ddot{x}+C_h(x,\dot{x})\dot{x}+K_h(x)+\dot{d} \tag{8}$$

Where $\theta_h(x)$ is the symmetric positive definite inertia matrix of the affected limb, $C_h(x,\dot{x})$ the limb's Coriolis force and centrifugal force matrix, K_h for a rigid array, $\dot{d}$ for interference, f_h^* for patient movement intentions, f_h the limb output force [9].

The control structure of this paper contains two feedback loops [18]. The internal feedback closed loop is based on the

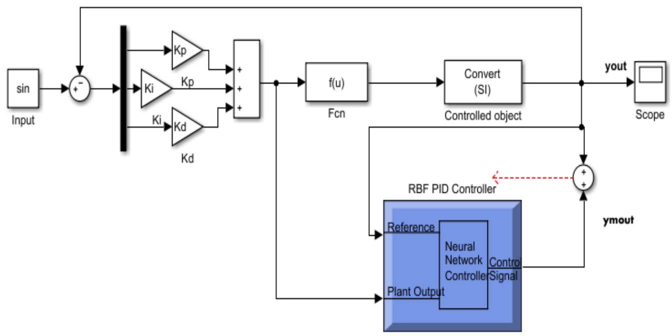
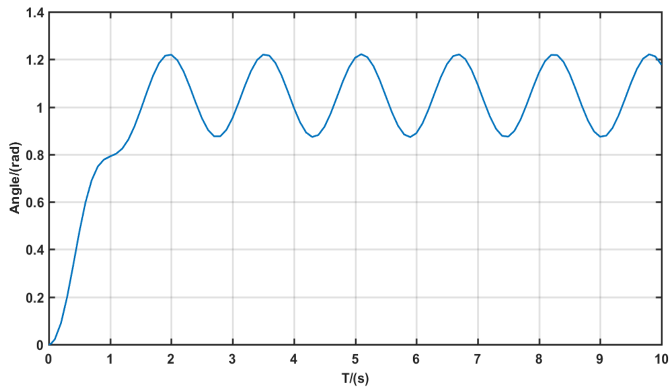
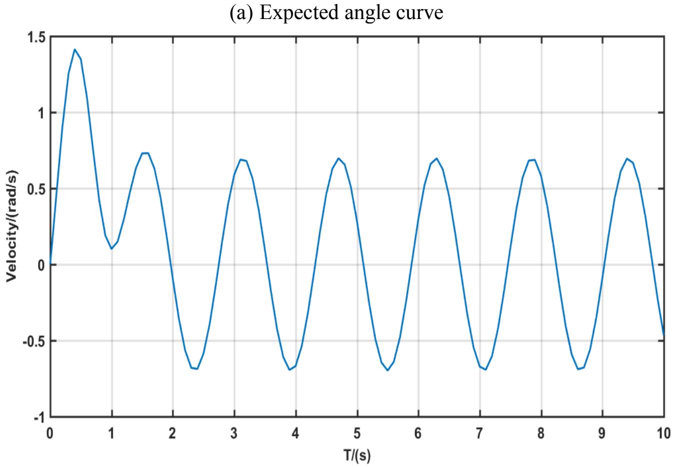


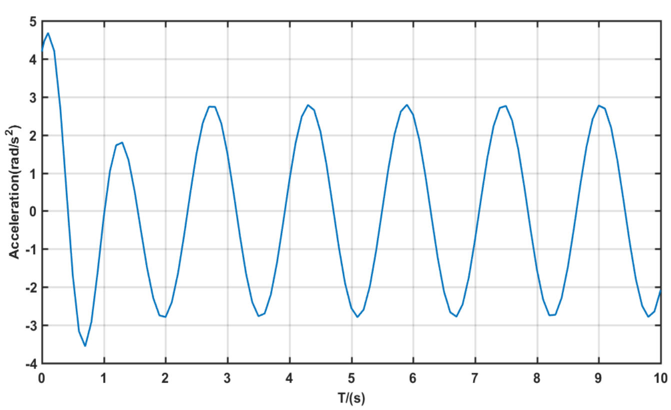
Fig. 6 Feedback linearization control algorithm structure diagram



(a) Expected angle curve



(b) Expected angular velocity curve



(c) Expected angular acceleration curve

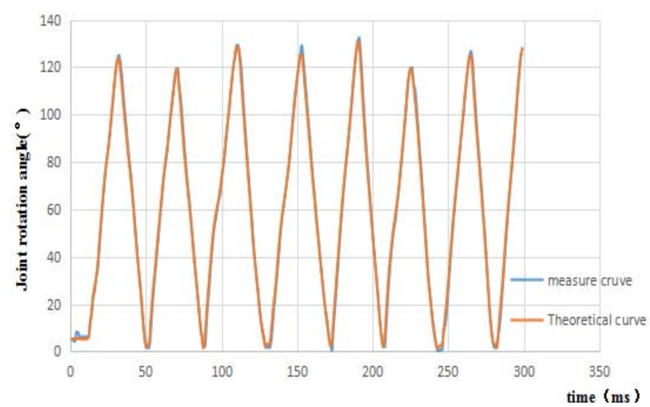
Fig. 7 Simulation results of the expected dynamic characteristics of the curve

robot dynamics model design. The disturbance torque generated by the nonlinear term during the robot motion is calculated, and the calculated nonlinear disturbance torque feedback is compensated to the torque input end. The purpose is to eliminate the nonlinear term of the robot. The resulting disturbance results in a decoupled linear system, the external feedback closed loop is used to eliminate the trajectory tracking error and can be used to stabilize the system [19]-[21].

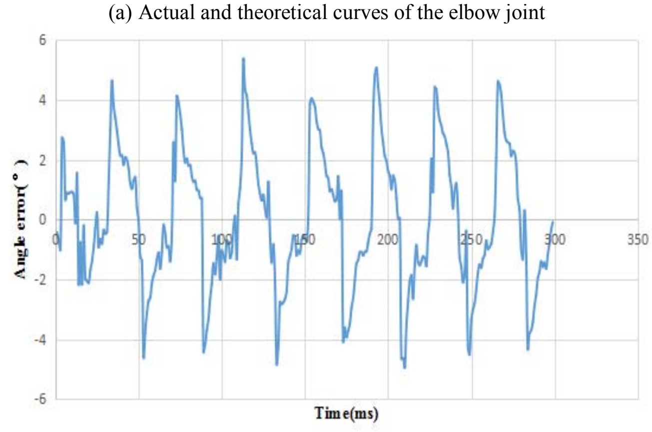
In the MATLAB simulation module Fig.6, the curves of the Angle, angular velocity, angular acceleration of the relevant target curve with time can be obtained as shown in the Fig.7.

The angle signals were acquired by an encoder and a gyroscope during the experiment. Fig.8 is the comparison between the measured curve and the theoretical curve of the elbow joint (set value range: 0~135°, error range: -6°~6°), and the corresponding error analysis diagram is made; Fig.9 and Fig.10 diagram are the wrist joint expansion and rotation contrast curve and error analysis (set value range: 0~90°, error range: -6°~6°).

It is proved by the experimental results that the RBF neural network control system is effective for controlling the controlled object in this paper, and the accuracy of the mechanical structure is improved by 9° under the conventional PID control.

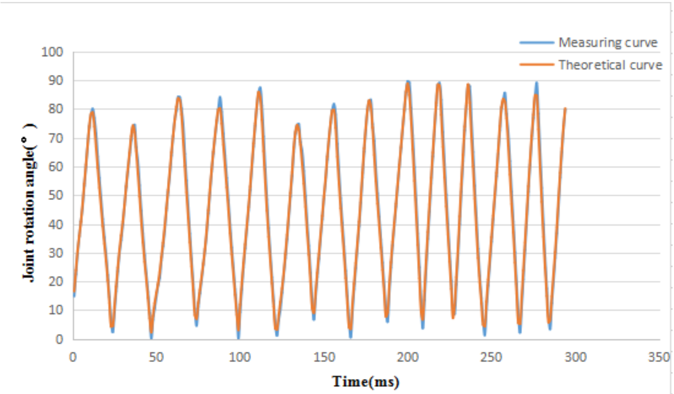


(a) Actual and theoretical curves of the elbow joint

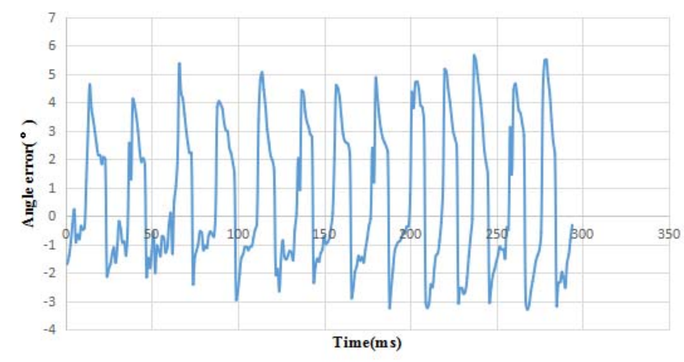


(b) Error in the results of the elbow joint experiment

Fig. 8 Three-degree-of-freedom elbow joint experimental verification diagram

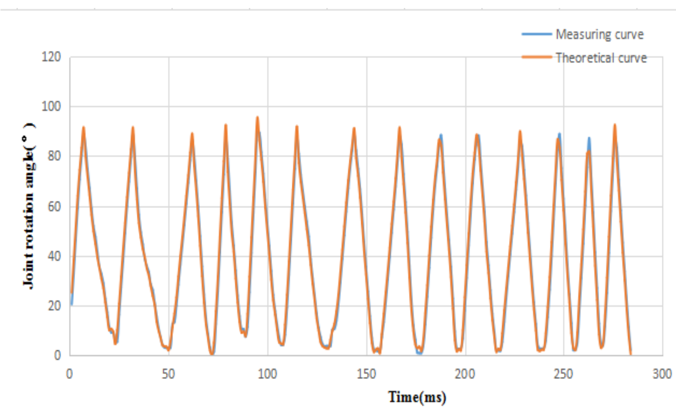


(a) Wrist joint actual and theoretical curve

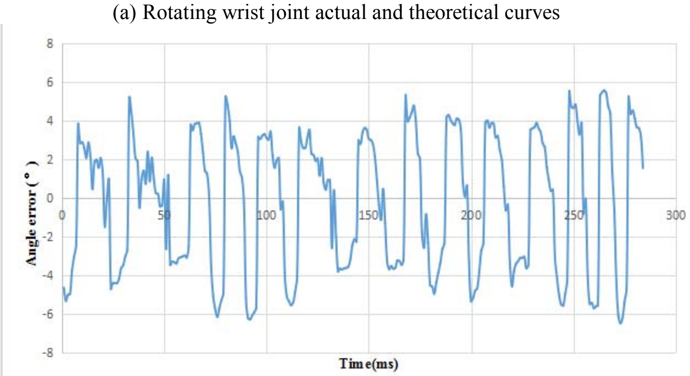


(b) Error in the results of wrist joint experiment

Fig. 9 Three-degree-of-freedom wrist joint experiment verification diagram



(a) Rotating wrist joint actual and theoretical curves



(b) Error in the results of wrist joint rotation test

Fig. 10 Three-degree-of-freedom rotating wrist joint experimental verification diagram

Ⅳ. Conclusion

Recently, it has been a hot spot for patients with hemiplegia to rely on such medical equipment for recovery. Rehabilitation robotic equipment has also been favored by researchers. In this paper, the static analysis of the designed exoskeleton equipment is firstly carried out to obtain the maximum stress, and the purpose is to reduce the burden on patients with weight reduction. According to the stress distribution effect diagram of the ANSYS analysis results, a suitable material can be selected to process the physical object. Then this paper proposes to use the RBF controller to test the control effect of the controller in the paper through MATLAB simulation experiment. According to the error graph in the previous chapter, the error completely satisfies the proposed error range of 15°, and the accuracy is improved by 3°. The comparison between the actual curve and the theoretical curve gives a good control effect of the controller. In general, the patient's wearable device can be made lighter by static analysis, overcoming the disadvantages of heavy weight. The RBF controller not only improves the control accuracy, but also improves the stability during the experiment to ensure the stable operation of the system. It also meets the characteristics of the exoskeleton wearable robot, allowing more patients with hemiplegia to receive timely treatment.

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