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Cable-driven Wearable Upper Limb Rehabilitation Robot

Ke Shi, Aiguo Song, Ye Li, Changcheng Wu

Abstract—**The usage of rehabilitation training robot is an effective way for postoperative stroke rehabilitation. The existing robots for upper limbs rehabilitation training are mostly designed with rigid links, which are large in size, high in cost and not easy to be aligned with human joints. This paper has developed a cable driven wearable 3-DOF (degree of freedom) upper limbs rehabilitation robot based on 3D printing structure, which has the characteristics of lightweight, personalization and low cost. For this robot, the kinematics modeling analysis is carried out, the position control method is designed, and the motion characteristics of the set trajectory are verified by dummy arm.**

I. INTRODUCTION

In recent years, the number of stroke patients has increased in the world. The stroke patients are generally paralyzed of upper and/or lower limbs, so they must be treated by regular sessions with a dedicated physical therapist in order to regain motor function[1]. Traditional rehabilitation training which is usually performed by therapists assisting patients with physical training has high requirements for therapists and high costs. With the increasing demand for rehabilitation training, the lack of therapists are exposed. Rehabilitation training by robots has become an effective method to solve this problem with the development of robot science[2].

Since the advent of the first assisting rehabilitation training device, a large number of rehabilitation training robots have emerged, such as MIT-Manus, MIME, ARMin, CAREX and so on[3][4]. The emergence of these robots has reduced the cost and improved the efficiency of rehabilitation training. However, most of existing robots for rehabilitation training are large, expensive and usually placed in the rehabilitation center. If rehabilitation robots could safely reach in-home use, cost would be reduced. Arm exoskeletons can be used for training in skeletal joint space, which have higher flexibility compared with end-effector type robots. Conventional arm exoskeletons such as ARMin, RUPERT, L-EXOS, EXO-UL7 are designed with rigid links connecting to human body[5].

There are some problems with this type of robots. On the one hand, the joint axes of arm exoskeletons need to be aligned with human joints to keep patients safe during the rehabilitation training. But it is difficult to achieve over the range of motion (ROM) of the arm because the axes of the human joints, which are formed by pieces of bones sliding and rotating relative to each other, change relative to the exoskeleton body segments[4]. On the other hand, arm exoskeletons are usually formed by metal structure and motors with large reduction gear ratio to support the body of patients and its own weight. This results in a large restriction on the physical movement of the patients, reduction of the training comfortability, and increase of the manufacturing cost[5].

To make exoskeletons lighter and wearable, some new designs are reported that are cable based. For example, Jin designed a 7-DOF (degree of freedom) cable driven upper limbs rehabilitation robot CAREX-7 to assist patients in arm rehabilitation training [3]; Cui created CDWRR which are cable based to realize the function of wrist and forearm rehabilitation[6]; Ignacio Galiana designed a wearable soft shoulder rehabilitation robot to assist in abduction/adduction degree of shoulder joint[7]. But these robots are massive [3] or not very practical with less DoFs [7].

This paper describes the design, kinematic analysis and experimental validation of a personalized, soft and wearable arm rehabilitation robot in low cost aimed at providing active/passive training model in the shoulder abduction/adduction, flexion/extension and elbow flexion/extension DOFs. The main structure is made of polyamides by 3D printing, with a small amount of metal components, which is in low cost and light weight, and can be designed according to the size of patient's body. This robot driven by the Bowden cables eliminates the possibility of injury that is caused by misalignment to the patients and improves the comfortability of patients in the rehabilitation training process. The arm gesture which is gotten from IMU sensors and cable tension which is acquired from tension sensors fixed on the cables are combined to be used to control the motor.

Section II describes the whole structure of the robot, including the mechanical structure and the hardware of the sensing control system. Section III describes the kinematic model and workspace of this robot. Section IV describes the PD control algorithm based on the position and introduces the active training model control method based on the arm gesture and cable tension. Section V describes the motion characteristics of the set trajectory by simulation mechanical arm and Section VI summarizes conclusions.

II. SYSTEM CONCEPT

The main structure of this robot is made of polyamides by 3D printing, which can be customized according to the size of patient's body and the requirement of rehabilitation training. So this robot adjusts to the body well in low cost and light weight. As shown in Fig.1, the main structure consists of five

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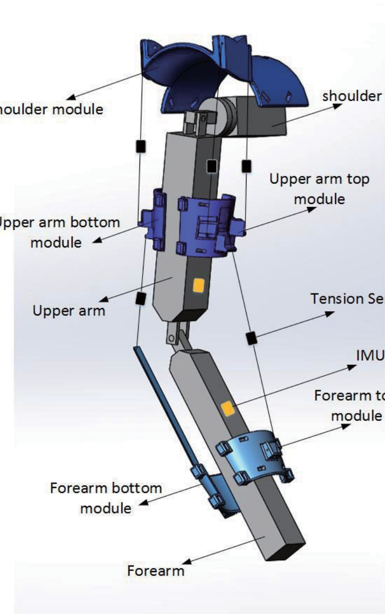
parts: shoulder module, upper arm bottom module, upper arm top module, forearm bottom module, forearm top module. According to previous work on cable driven robot, the shoulder module and the upper arm modules must be connected by three cables to achieve the function of training in abduction/adduction and flexion/extension DOFs of shoulder joint[8]; the upper arm modules and the forearm modules must be connected by two cables for training of the flexion/extension DoF of elbow joint. The independent cables in elbow joint make the elbow motion control completely separated from the shoulder joint movement, increase the effective workspace and reduce the complexity of robot control.



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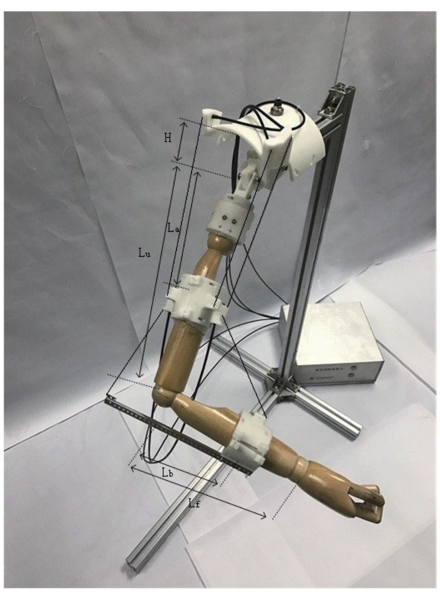


(b)

Fig.1 The 3D model and prototype of the robot

As shown in Fig.1(a), the joints between cables and modules are especially thick to keep the strength of 3D printing material. Both the forearm and upper arm modules consist of the top and bottom parts, which are fixed together by nylon tapes and easy to wear for patients. The inner side of each module is soft foam filled material which is comfortable for patients in contact surface to modules and eliminates the possibility of injury caused by friction and pressure. There is a light L metal rod fixed on the forearm bottom module which lengthens the module to avoid the interference between the cable and the arm when the angle of elbow joint is large (more than 20 degree). In the same way, the shoulder module fixed on the shoulder extend outward to increase the pull arm of cables to avoid the interference between the cable and the arm during the training. Every modules and patient's body are connected by soft belts to keep each module fixed and avoid relative sliding caused by tension on the cables between modules and body. The arm gesture which is gotten from IMU sensors fixed on forearm and upper arm modules and cable tension which is acquired from tension sensors fixed on the cables are combined to be used to control the motor. This system is driven by five light MAXON RE25 electric motors with encoder to acquire the length of cables to initialize and control the robot. Total weight of this robot without motors and control box is about 500g.

III. Kinematic Analysis

This rehabilitation robot provides active/passive training model in the shoulder abduction/adduction, flexion/extension and elbow flexion/extension DOFs. As shown in Fig.2, there is the kinematic model of this robot.

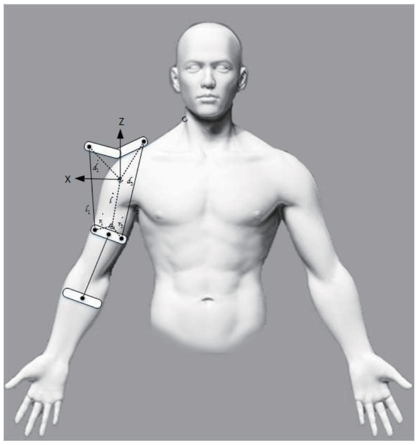
$\vec{l}_1, \vec{l}_2, \vec{l}_3$ is from the attachment points of upper arm modules to shoulder module; $\vec{r}_1, \vec{r}_2, \vec{r}_3$ is from the attachment points of upper arm modules to the section center of upper arm; $\vec{l}$ is from the section center of upper arm to the center of shoulder joint (the shoulder joint is equivalent to spherical joint); $\vec{l}_4$ is from the attachment points of forearm modules to upper arm modules; $\vec{r}_4$ is from the attachment points of forearm modules to the center of elbow[7] [9]. So the torque/force of shoulder joint can be calculated by:

$$\begin{bmatrix} F_S \\ T_S \end{bmatrix} = \begin{bmatrix} \frac{\vec{l}_1}{|\vec{l}_1|} & \frac{\vec{l}_2}{|\vec{l}_2|} & \frac{\vec{l}_3}{|\vec{l}_3|} \\ \frac{\vec{l}_1}{|\vec{l}_1|} \times (\vec{r}_1 + \vec{l}) & \frac{\vec{l}_2}{|\vec{l}_2|} \times (\vec{r}_2 + \vec{l}) & \frac{\vec{l}_3}{|\vec{l}_3|} \times (\vec{r}_3 + \vec{l}) \end{bmatrix} . \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} \quad (1)$$

The torque/force of elbow joint can be calculated by:

$$\begin{bmatrix} F_E \\ T_E \end{bmatrix} = \begin{bmatrix} \frac{\vec{l}_4}{|\vec{l}_4|} \\ \frac{\vec{l}_4}{|\vec{l}_4|} \times \vec{r}_4 \end{bmatrix} . [T_4] \quad (2)$$

$$\begin{bmatrix} F_S \\ T_S \end{bmatrix} = \begin{bmatrix} f_x \\ f_y \\ f_z \\ \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} \quad (3)$$



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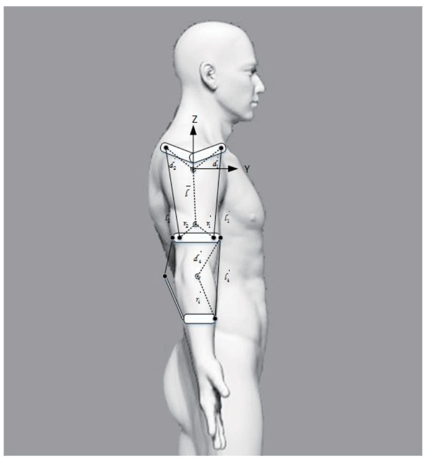


(b)
Fig.2 Kinematic model

To keep the training security, the cable tension bounds are set between 2N to 80N. Meanwhile, the maximum joint angular velocities are set as 0.1rad/s. Previous work shows that shoulder joint is not just a simple spherical joint but consists of a series of complex parts, so its rotating center changes during the movement[10]. In this paper, the shoulder joint is simplified into spherical joint to make the kinematic model simple [9]. Especially, the arm of patient is usually fixed with the exoskeleton which is rigid structure robot. The movement of the arm will be interfered because of the misalignment between the joint center of robot and human, which reduces the comfortability of training and leads to injuries. Obviously, this problem is avoided because the arm of human is part of the cable driven robot. In this model, the length of cables can be acquired by the encoders on motors; the radius of the arm section is known during measurement for module customization.

Because of the structure of this robot, the workspace cannot reach the maximum range of human joint motion. But it is enough for some active daily living training (drinking, writing, etc.) except shoulder joint internal/external DoF and wrist joint DoFs. The range of shoulder joint abduction/adduction: 0~80°, flexion/extension: 0~90°, and elbow joint abduction/adduction: 0~120°. The independent Bowden cables in elbow joint make the elbow movement completely separated from the shoulder joint. As shown in Fig.3, there is accessible location of the elbow joint center during this system works.

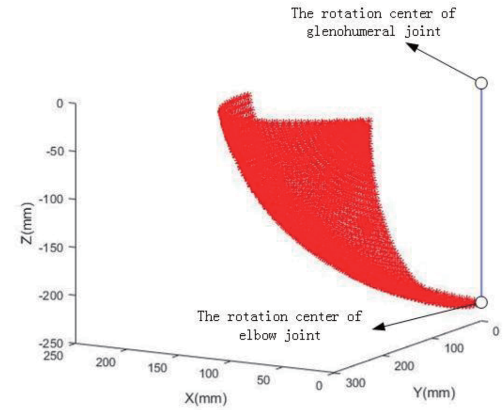


Fig.3 The workspace

IV. CONTROL ALGORITHM

Usually, the rehabilitation robot control algorithm is based on force. During the passive training according to the set trajectory, the control errors based on force are much greater than that based on position on account of the characteristic of the cable driven robot. And the control based on position is still security for patients because of this soft characteristic. Therefore, for passive training model of this robot system, the PD control algorithm based on position is applied. As shown in Fig.4, there is the control diagram of passive training model. The cable length is calculated according to the position of modules and the gesture of arm. The tension sensors are used to acquire the real-time tension of cables to keep patients safe during the training [3]. The cables movement can be calculated by:

$$\vec{l}_n = \vec{r}_n + \vec{d}_n + \vec{l}\,(n = 1,2,3) \tag{4}$$

$\vec{d}_n$ is from the rotating center of shoulder joint to the attachment points of shoulder modules, and all of the vectors are in the coordinate whose origin is S.

Because the elbow movement which only includes flexion/extension DoF is completely separated from the shoulder joint, the equation can be given:

$$\vec{l}_4 = \vec{r}_4 + \vec{d}_4 \tag{5}$$

$\vec{d}_4$ is from the rotating center of elbow joint to the attachment points of upper arm modules, $\left|\vec{l}_4\right|$ is only relative to the angle of elbow joint.

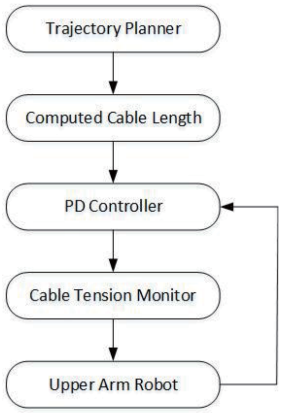


Fig.4 Control flow chart

As described above, the rotating center of shoulder joint changes during the movement, and it cannot be calculated accurately. The change causes the errors when the control algorithm is based on position. But the errors are usually small and the security of training will not be affected. It is supposed that there is the change of the rotating center of shoulder joint, and the training trajectory is set as shown in Fig.5. The change of the rotating center of shoulder joint is set according to [11] . The angles of each DoF are shown in Fig.6. γ is the angle of flexion/extension DoF of elbow joint, and the positive direction is flexion; α is the angle of abduction/adduction DoF of shoulder joint, and the positive direction is abduction; β is the angle of flexion/extension DoF of shoulder joint, and the positive direction is flexion. The arm movement trajectory is calculated according to the model above with the change which is in positive correlation with the angle of shoulder joint added in randomly. As shown in Fig.6, there is no error of γ , and the maximum error of α and β is less than 10%.

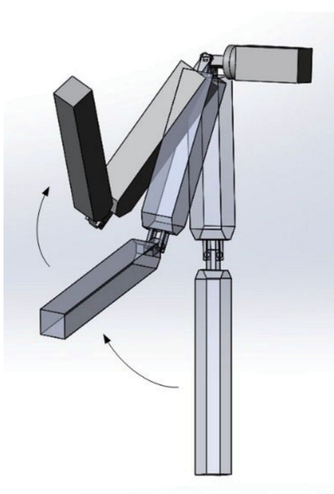


Fig.5 Simulated training trajectory

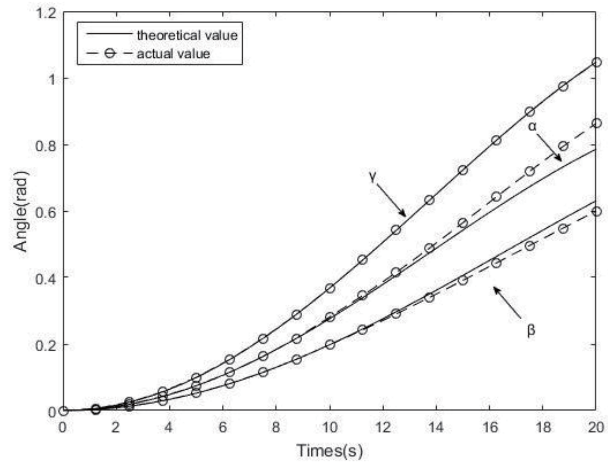


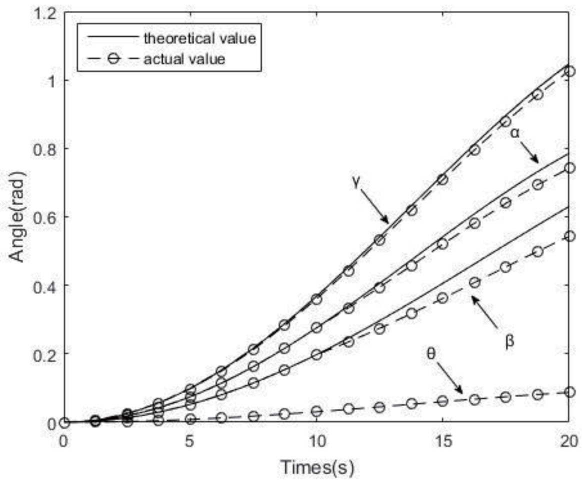
Fig.6 Simulation result

For active or assistive training model, the weight compensation of the arm is necessary[3]. Because it is easy to calculate the tension of cables between the upper arm and forearm modules according to gesture of the arm, the weight compensation of forearm can be achieved. However, for upper arm, the cables tension is difficult to calculate because the change of arm gesture and the center of gravity. The weight compensation model based on GRNN which is applied to achieve the active training model based on cables tension and arm gesture will be shown in future papers[12].

V. Experiment and Analysis

The experiment of the dummy arm which has the same DoFs with human arms is designed to verify the motion characteristics of this robot. As shown in Fig.1(b), this dummy arm has three DoFs in shoulder joint and one DoF in elbow joint; the length of upper arm is Lu=0.330m; the mass of upper arm is Mu=2kg; the length of forearm is Lf=0.320m; the mass of forearm is Mf=1.8kg. The shoulder module is fixed above the shoulder of the dummy arm (H=0.070m); the upper arm modules is L_a=0.180m away from the rotating center of shoulder joint; the forearm modules is L_b=0.150m away from the rotating center of elbow joint. There are IMU sensors on each module to acquire gesture of the arm.

The robot working parameters are set according to the trajectory given in last section. The angles of each DoF is shown in Fig.7(a), and θ is the angle of internal/external DoF of shoulder joint. The change of cable length starting from the initial position is shown in Fig.7(b). By comparing the actual curve with the theoretical, there is small angle error of elbow joint (less than 5%), while there are greater angle errors of three DoFs of the shoulder joint (about 10%). Obviously, these errors cannot be caused by the change of rotating center because the rotating center of dummy arm shoulder joint cannot move. The errors of three DoFs are caused by the change of angle θ which cannot be completely controlled in this version of the robot[6].



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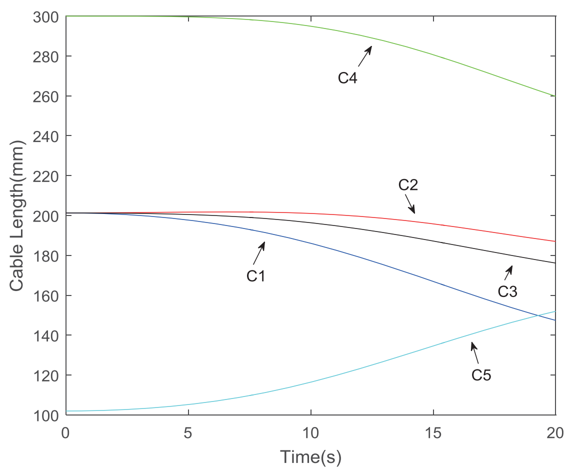

(b)

Fig.7 Experiment results by the dummy arm

VI. CONCLUSION

This paper has developed a cable driven wearable 3-DOF upper limbs rehabilitation robot based on 3D printing structure, which has the characteristics of lightweight, personalization and low cost [3].

The passive training is achieved based on PD control algorithm. There are angle errors of shoulder joint because the position of rotating center changes during the movement and the internal/external DoF of shoulder joint cannot be completely controlled in this version of the robot. In future research, the new model based on RBF neural network will be set to acquire the change of rotating center of shoulder joint. The weight compensation model based on GRNN will be applied to achieve the active training model based on cables tension and arm gesture.

During the experiment of dummy arm, the internal/external DoF rotation which cannot be controlled causes angle errors of abduction/adduction and flexion/extension DoFs. In late-stage study, the structure will be optimized to control the internal/external DoF to enhance the function of this robot.

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