Multi-Arm lower-limb rehabilitation robot for motor coordination training after stroke

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Abstract: The number of stroke patients is rapidly increasing in the elderly society, which leads to growing demand for lower limb rehabilitation training. Currently, one patient needs two or more therapists for assistance during gait training. It results in the shortage of therapists’ population, furthermore, heavy works load on the therapist. The emerging robotic technologies provide a solution to assist the therapist, and a number of corresponding researches have been reported. However, most of the existing rehabilitation robots adopt single-arm or double-arm structure, which pays less attention on motor coordination training for the stroke patients. Here, a four-arm rehabilitation robot (FARR) is proposed to assist the hemiplegic patient for motor coordination training. First, the rehabilitation demand is analysed and the corresponding robot mechanism is designed. Then, the kinematics of the robot based on the D-H expression is constructed, and the workspace is obtained. Thirdly, the speed control strategy and the cooperative control for gait training are constructed. The experiment of speed response verifies the superior tracking performance of the robotic joints, and the experiment of using the robot for gait training by a simulated subject is performed. These results prove the feasibility of the designed robot.

1 Introduction

Stroke is a serious injury to human health, especially to aged population characterised by high incidence and recurrence rate. About 75% of survivors after stroke suffer disability. The incidence of stroke has continued to increase recently [1]. Patients usually suffer from hemiplegic sequelae after the stroke and spend extended periods to recover the nerve function. In traditional rehabilitation training, each patient must be accompanied with a professional therapist, which increases his/her workload. Thus, more attention needs to be paid on the elderly service and rehabilitation industry worldwide [2]. It is proposed by many research institutes that the robotic device can assist the rehabilitation of patients. Due to irregular rehabilitative exercise executed by traditionally manual operation. For example, therapists with different operative experiences lead to uniform training and evaluation. The high cost increases the financial burden of patients. Furthermore, each patient needs at least one therapist during rehabilitative exercise, which increases the workload of the therapist. Most of the existing robot platforms adopt passive training and are unable to exert patients’ subjective initiative during training reducing the effectiveness of rehabilitation. Moreover, the difference of the individuals and the rehabilitative stages required that the device should be quickly adjusted and mounted, which is still the inferior of the existing prototypes.

The existing lower limb rehabilitation robots include the single weight support robot, the pedal robot, the bed robot, as well as the exoskeleton robot. The weight support robot mainly aims to reduce the weight of patients, such as the US Kine Assist [3] and Japanese robotics [4]. The instance of Pedal-type robots including the German Gait Trainer [5–7], Haptic Walker [8], Gait Master [9], Chengdu University [10], and Harbin Engineering University [11] are trapped in large volume and loss of the automatic detection system. They rely on the therapist to adjust the training parameters, resulting in an additional workload for the therapist.

Bed-based rehabilitation robots, such as Swiss Erigo [12], can play a significant role in the early period of rehabilitation intensive training. However, the motion angle of the robotic joint is limited, and the robot cannot automatically adjust its function according to the rehabilitative state of the patient who needs further improvement. The exoskeleton robots have become a hot spot, such as the Lokomat in Switzerland [13], Lucy in the USA [14], and HAL in Japan [15]. Many universities in China also have developed the exoskeleton robots, including Tsinghua University [16], Shanghai University [17], Harbin Engineering University [18] etc. Nevertheless, they cannot accurately collect the feedback of patient information due to accumulated error coursed by wearing device. Moreover, the robot is cumbersome and time costing for wearing and adjustment. Hence, the shortcomings limit the application of the exoskeleton robot in the real rehabilitative circumstance. The design of the most existing rehabilitation robots is based on the motion model of healthy subjects. There is a great gap between the rehabilitation training methods and the therapist techniques, which makes it difficult for doctors to understand the patient’s state and formulate individual training programmes. This paper innovatively takes the therapist as the research object and explores the critical technologies of rehabilitation robots, which begin with the biomimetic simulation of therapist’s operative practice. A four-arm rehabilitation robot (FARR) (Fig. 1) has been developed to mimic the skills of a therapist to meet the rehabilitative needs of different patients and shorten the preparation time.

The proposed four-arm robot consists of two segments, including the upper dual-arm robot and the lower dual-arm robot. The dual-arm robot owns superior characteristics compared with the single-arm robot, with wider operation space and stronger load capacity, which has more outstanding stability, complexity, and reliability in operation [19]. Therefore, the dual-arm robot has attracted the attention of many scholars and achieved certain achievements. For example, Japanese ASIMO [20], HRP-2robot.
with reference to the human body's database. The space movement track of the right hip is shown in Fig. 3, which can be used to underwater manipulator by numerical method. However, these imitates the operation of the therapist and performs rehabilitation torso support mechanism, and lower limb support mechanism. In workspace mainly includes geometric method, analytic method, mainly consists of shoulder joint, elbow joint, and wrist joint [24], humanoid robots in China, and the cymbal robot [25] and so on. Kinematics and workspace analyses are the basis of robot motion planning and control. At present, the solution of robot workspace mainly includes geometric method, analytic method, and numerical method. Jiang Y. et al. [26] solved the workspace of IRB140 robot by geometrical method, Khiar et al. [27] used the Jacobian matrix to solve the workspace of multi-joint robots, Zhong yong et al. [28] calculated the workspace of sw-ru underwater manipulator by numerical method. However, these researches mainly focused on the workspace of two-arm robots' cooperative motion.

2 Mechanical design

2.1 Demand analysis

According to the theory of brain plasticity and functional reorganisation, motor functional rehabilitation could be realised through early-stage training [29–31]. The restoration of lost motor function has been restricted in most biomedical treatments [32]. It just has partial effects on functional motor recovery through physical therapy [33, 34]. The FARR simulates the rehabilitation techniques of the therapist while guiding the patient to participate in the training actively and improving the performance of recovery. Corresponding to the physiological structure of therapist's arm mainly consists of shoulder joint, elbow joint, and wrist joint (Fig. 2), a simplified model of four-arm robot is established, which imitates the operation of the therapist and performs rehabilitation training to the patient.

In order to regain the walking capacity after stroke, the FARR is used to simulate the support operation of the therapist and assist the patients in the gait rehabilitation training. The posture quaternion of the lower limb is obtained by using the motion detection system. Therefore, the trajectory of the torso and buttocks is calculated with reference to the human body's database. The space movement track of the right hip is shown in Fig. 3, which can be used to control the trajectory of the distal of the manipulator.

2.2 Mechanical structure

The FARR system is mainly composed of elevator mechanism, torso support mechanism, and lower limb support mechanism. In addition, the core unit of FARR such as treadmill, weight reduction device, and suspension auxiliary device has been shown in Fig. 4. The mechanical arm has three active degrees of freedom (DOF), which enable manipulator to move up/down, left/right, front/back, while another three passive DOFs of spherical joint at the end of the manipulator are set to offset the transformation caused by the patient's posture change relative to the manipulator.

The FARR is required to provide large payload to assist patients in the early rehabilitative stage. In the early stage, the patient's muscle strength is weak, the robot needs to bear most of the patient's weight during the training. Therefore, the requirements for safety and driving force are very high. In addition to the use of weight reduction mechanism and suspension device, the harmonic reducer having a small volume, high security, and large transmission ratio reducer is also adopted at each joint. The motor has a brake function, which ensures personal safety when running false or accidental power failure.

2.3 Control system

The control system (Fig. 5) of the FARR is to serve as the basis for realising the upper control instructions in the mechanical structure and as a bridge for communication between users and rehabilitation robots. Furthermore, the implementation of control instructions directly affects the realisation of rehabilitation training functions and the evaluation of the ultimate rehabilitation effects.

Using FARR to carry out rehabilitation training not only needs to control the position precision of the single arm, but also ensures the accuracy of the simulation of the therapist's rehabilitation technique. In view of the cooperative rehabilitation operation of multiple therapists in the rehabilitation process and the state full of uncertainty of patients, the rehabilitation robot must carry out the cooperative control among multiple robotic arms, so as to accurately simulate the cooperative rehabilitation operation of multiple therapists. A further demonstration is needed in the application of collaborative control methods and strategies. In particular, how to deal with the multi-arm collaborative control model under the strong disturbance caused by abnormal movement of patients during rehabilitation remains to be a problem lacking practical verification. Therapists have outstanding performance of cooperativity in clinical situations. This paper will simulate this
after co-controller adjustment appears, the end track is produced by
Then, the forward kinematic solution to the robot is obtained from
case strategy for the reproduction of the therapist's cooperative
technique. Finally, the coordination of FARR is guaranteed, which provides
training model, as the input of collaborative control module.
3.1 Coordinate system establishment and parameter
determination
There are two kinds of coordinate systems to describe the
kinematics of the robot. One is the local coordinate system where the
coordinate system is used by each arm. The other is the global
coordinate system where the left and right arm local coordinate systems
are symmetric about the global coordinate system. According to the FARR
designed in this study, the model is simplified and the coordinate system is created, shown in Fig. 6, ‘R’ represents the number of links, i = 1…4, ‘L’ represents the right
arm, ‘L’ represents the right arm. Here, the left arm and the right arm are symmetrically configured. Hence, only the kinematics of
the right arm is described. The authors can confirm the D-H parameters refer to the linkage coordinate system. The three
motion pairs of the manipulator are rotating pairs, and the joint
variables are described as \( \theta_1 \), \( \theta_2 \) and \( \theta_3 \), respectively, the positive
direction of the variable and the corresponding Z-axis conform to the
right-hand rule. The manipulator is simplified to three
connecting rods, with the upper arm, the rotary mechanism and the
lower arm marked as \( \text{L} \), \( \text{L} \), and \( \text{L} \), respectively. The shoulder
support mechanism is marked as \( \text{L} \), and the grasping mechanism
fixed to the end of the arm marked as \( \text{L} \). (Note: \( \text{L} = 150 \text{ mm}, \text{L} = 114 \text{ nm}, \text{L} = 274 \text{ mm}, \text{L} = 253 \text{ mm}, \text{L} = 40 \text{ mm} \). Based on the
above coordinate system and the specific geometric parameters of
the manipulator, the corresponding D-H parameters are presented
in Table 1.

3.2 Forward kinematics calculation and spatial analysis of
manipulator
The essence of forward kinematics analysis is the coordinate
transformation. The fundamental task of kinematics analysis is to
obtain the transformation matrix between the reference coordinate
system and the terminal coordinate system. The transformation
formula between near two coordinate systems is as follows:

\[
\begin{bmatrix}
C\theta_i & -S\theta_i & 0 & a \\
CaS\theta_i & CaC\theta_i & -Sa & -dSa \\
SaS\theta_i & SaC\theta_i & Ca & dCa \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

(1)

\[
S\theta_i = \sin \theta_i \quad C\theta_i = \cos \theta_i
\]

Based on the transformation of adjacent links, the transformation
coefficients between the 0-coordinate system and the 4-coordinate
system can be obtained by multiplying the coordinate systems of
the links in turn.

\[
q^T = q^T_1T_2^1T_3^2T_4^3T
\]

3 Kinematics analysis
Kinematics analysis is used to describe the geometric relationship
between the endpoint and the joint, and it is also the basis for
studying the robot workspace using the forward kinematics. Here,
first, according to Denavit–Hartenberg regulation, the authors
established the D-H coordinate system and confirmed parameters.
Then, the forward kinematic solution to the robot is obtained from
the general form of the linkage transformation of robotics. Finally,
analysing the workspace of the robot and calculating the solution of
inverse kinematics are conducted.

\[
\begin{array}{|c|c|c|c|}
\hline
\text{Link (i)} & \alpha_{i-1}^e & \theta_i & \theta_i \left(30° - 120° \right) \\
\hline
1 & 0 & 0 & -L0 \theta_i \left(30° - 120° \right) \\
2 & 90 & 0 & 0 \theta_i \left(30° - 120° \right) \\
3 & 90 & 0 & 0 \theta_i \left(30° - 120° \right) \\
4 & 0 & -L4 & L3 & 0 \\
\hline
\end{array}
\]

Note: \( \alpha_{i-1}^e \) – the rotation angle of the \( x_i \) axis around the \( x_{i+1} \) axis; \( \theta_{i-1}^e \) – the moving distance of the \( x_i \) axis along the \( x_{i+1} \) axis; \( \theta_i \) – the
rotation angle of the \( x_i \) axis around the \( x_{i+1} \) axis; \( d_i \) – the
moving distance of the \( x_i \) axis along the \( x_{i+1} \) axis.
and accuracy. The driver controls the brushless DC servo motor with the speed as the input variable of the speed control mode. PWM speed control system has advantages of fast, strong anti-interference ability, good low-speed performance and high stability and accuracy. The driver controls the brushless DC servo motor through close-loop (Fig. 8). The current loop directly adjusts the current size to control the torque of the motor, and the control precision at each target point. The root-mean-square error (MSR) of speed response. In addition, the driver set an interface to alter the speed and position characteristics. The results of this verification to single joint are shown in Fig. 9. The subplots Fig. 9a-c presents the control of the shoulder joint, upper arm, and elbow joint with different speeds. Here, ±2, ±4 and ±6 rpm is selected, respectively, in the transmission mechanism of movement. In the process of the transmission affected by the weight, inertia, and friction of mechanism, the speed of its movement exhibited fluctuation, with a good position accuracy. The forward flexion and extension of the manipulator could be adjusted to a stable state.

4.1.2 Experiment of speed response: This section implements an experiment with single joint motor control system and presents the speed and position characteristics. The results of this verification to single joint are shown in Fig. 9. The subplots Fig. 9a-c presents the control of the shoulder joint, upper arm, and elbow joint with different speeds. Here, ±2, ±4 and ±6 rpm is selected, respectively, in the transmission mechanism of movement. In the process of the transmission affected by the weight, inertia, and friction of mechanism, the speed of its movement exhibited fluctuation, with a good position accuracy. The forward flexion and extension of the manipulator could be well completed by the transmission mechanism and quickly adjusted to a stable state.

4.2 Position control of single arm

The control strategy of single mechanical arm is shown in Fig. 10, first, trajectory planning is designed to obtain the position of each joint by means of the inverse kinematics. The obtained position is used as the input of position control of brushless servo DC motor; The actual trajectory of the end of the manipulator which is related to the desired position precision is the accumulation of the position precision at each target point. The root-mean-square error (MSR) of each point is expressed as follows:

$$\Delta = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (P_i - P_{Ref})^2}$$

Note: $P_{Ref}$-Target space trajectory; $P_T$-Actual space trajectory.
The spatial position trajectory of the end of the manipulator is shown in Fig. 11. Due to the influence of the inertia from the manipulator and the algorithm of position calculation, the actual space trajectory has a specific deviation from the target trajectory, \( \Delta = 0.81 \). The manipulator has good positioning accuracy.

4.3 Cooperative control experiments of dual-arm

The experiment aims to verify the cooperative control of the dual-arm. The target trajectory of the active manipulator is a space circle and the actual trajectory of the passive manipulator is symmetric with the active manipulator about a space point. The RMSE is used to evaluate the position precision. The spatial position trajectory of the end of the dual-arm is shown in Fig. 12. The position error of
active arm is $\Delta = 0.85$. As of the position precision of the active manipulator, there is a certain deviation between the space trajectory of the manipulator and the target trajectory, $\Delta = 1.19$. The dual-arm have good coordination control position accuracy.

4.4 Experiment of gait training

The FARR needs to be tested in practical experiments to verify whether gait training satisfies requirements, including the centre of gravity transferring and station transferring. In order to avoid secondary injury and reduce unnecessary experimental verification of suspension and other systems, Fig. 13 expresses the FARR control strategy. This experiment is mainly about functional verification experiments of the supported gait training by selecting healthy people as subjects. There is no need to prepare suspension and weight loss device, because healthy people have a better capacity of weight support. The left supported manipulator is Active-I, the left manipulator of body attitude control is Active-II. In addition, the right arm of lower limb support and trunk attitude control is from Passive-I and Passive-II, respectively (Fig. 14). First, experimenter stood naturally with his feet apart. In the experiment, Active-I follows the target trajectory of hip joint. Then, the Active-II and Passive-I follow the actual trajectory of Active-I based on their respective controlling strategies. Furthermore, Passive-II follows the actual trajectory of Active-II according to its own controlling strategies. The position curve of gait under the support of this machine is shown in Fig. 14b. On the basis of analysis of experimental results, the MSR of each manipulator can be obtained which is shown $\Delta_{\text{Active-I}} = 0.7947$, $\Delta_{\text{Active-II}} = 0.8781$, $\Delta_{\text{Passive-I}} = 1.16$, $\Delta_{\text{Passive-II}} = 1.62$. According to the MSR of each manipulator mentioned above, the conclusion can be drawn that each manipulator of lower limb rehabilitation robot can realise corresponding position control to support patients achieve walking training.

5 Conclusion and future work

With the increasing population of the stroke, the demands of rehabilitation training for the stroke survivors are continually growing. Here, a four-arm structure rehabilitation robot (FARR), which consists of two torso support arms and two lower limb support arms, was designed to assist the stroke survivors recover their motor abilities. Based on the kinematical expression, the workspace of the designed robot was calculated. The speed response of each single joint of the FARR was tuned, and then, a cooperative control strategy for gait rehabilitation was constructed. The experiments of cooperative control of the FARR demonstrate the good tracking performance among the four arms, and the preliminary experiment of the FARR with a healthy subject illustrates the feasibility of the designed robot system.
A number of extensions to this work will be done in the future. A major improvement of the designed system is to consider the human–machine interaction behaviour to reduce the hidden risk for patient safety. Force sensors will be mounted into the human–machine interface to collect the interaction force, which feedbacks to the control system for patient gait training. Comprehensive clinical trials with the designed FARR will be conducted to verify the performance of the FARR in the real rehabilitative circumstance.

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