

Kinematics analysis, design, and simulation of a dual-arm robot for upper limb physiotherapy

Siqi Cai^a, Guowei Huang^b, Ledeng Huang^c and Longhan Xie^{d,*}

Shien-Ming Wu School of Intelligent Engineering, South China University of Technology, China

Email:^a2447379329@qq.com, ^b616126836@qq.com, ^c289412708@qq.com,

^dmelhxie@scut.edu.cn

Abstract. Robot-assisted therapy offers a promising approach to rehabilitation, particularly for severely to moderately impaired stroke patients. This paper presents the Dual-Arm End-Effector-Based Rehabilitation Robot (DEREROB), which is a robotic system for upper limb physiotherapy including two co-operating robot arms. With this configuration, the robot arms of DEREROB are connected to the patient's upper arm and forearm respectively, which mimics the therapist's arms to provide the rehabilitation treatment. The kinematics model has been framed by D-H method and kinematics simulation has been carried out to verify that the DEREROB can assist the affected arm move in 3D space.

1. Introduction

Stroke is a leading cause of permanent disability worldwide and many stroke survivors have chronic unilateral motor dysfunction in the upper extremity that severely limits their functional movement control [1]. Many studies have demonstrated that early intensive therapies can enhance a patient's recovery but only 18% of stroke survivors regain full motor function after six months due to the limitation of traditional rehabilitation [2]. The training heavily reliant on one-on-one manual interactions with therapists, which is labor-intensive, time consuming and expensive. In contrast, robot-assisted rehabilitation for affected upper limbs have remarkably advantages in intensity, accuracy, efficiency and cost. Thus, there is increasing interest in developing rehabilitation robots and many rehabilitation robots have been used in the physiotherapy of hemiplegic patients after stroke. To allow rehabilitation training, a robot must be able to move the patient's arm in all relevant degrees of freedom in space, which can be achieved by an end-effector based robot or by an exoskeleton-based robot. For instance, ARMin I, II and III [3], CADEN-7[4] and RUPERT [5] are typical representatives of exoskeleton-based rehabilitation robots, while GENTLE/s [6], MIME [7] and ADLER [8] are end-effector based.

The structure of exoskeleton-based robots resembles the human arm anatomy; thus, it can measure the individual joint angle of the human arm more precisely. However, proper alignment between joint axes and exoskeleton-based robots axes is crucial, which makes it difficult to adapt to different arm lengths and may cause joint injuries of the patient's arm. In contrast, end-effector based robots, which are connected with the patient's forearm at one point, are easier to realize and adapt to different arm sizes. Therefore, many end-effector-based robots have been developed and most of them assist the affected arm move through a single attachment to the patient's arm. But the structure with a single attachment leads to a main problem, that is, an end-effector position can be the result of a number of different elbow and shoulder joints rotations. Considering that the shoulder girdle is a rather instable joint, applying a high shear forces to the shoulder joint may cause the humerus head dislocation.



Furthermore, hemiplegic patients will utilize compensation strategies with a single attachment-based structure and this is also the reason why therapists use both hands when they mobilize a spastic elbow joint. To address these problems, dual-arm rehabilitation end-effector-based robot has been proposed, such as REHAROB [9] and iPAM [10]. Both REHAROB and iPAM use two industrial robots provides rehabilitation training through two attachments to the upper and lower arms of the hemiplegic patient respectively. But using industrial robots as rehabilitation robots has some shortcoming; For instance, the gross motions of rehabilitative robots are always slow and accelerations are also lower than in industrial applications. Moreover, REHAROB used a permanent fixture which cannot be flexibly deployed and iPAM is based on two 6-DOF industrial robots which makes the whole system complex and expensive.

To address the limitations, a brand new dual-arm end-effector-based rehabilitation robot, which has two manipulators connecting to the upper and lower arms of the hemiplegic patient respectively, was proposed in this paper. First, mechanism design based on the requirements for an upper limb rehabilitation robot was presented. Secondly, Mathematical model of kinematics analysis of this robot was established and verified. Thirdly, kinematics simulation results, which indicates the feasibility and effectiveness of this robot to assist hemiplegic upper limb with rehabilitation, were given. Finally, conclusions were drawn.

2. Kinematics Design

The goals of the design of the Dual-Arm End-Effector-Based Rehabilitation Robot (DEREROB) is to imitate the therapist's arms and assist the hemiplegic upper limb with rehabilitation training in 3D space. To develop a rehabilitation robot, many medical aspects should be taken into consideration, such as the segment lengths, range of motion (ROM) and the number of degrees-of-freedom (DOF) of human arms. Since it's easy for end-effector-based robot to adapt to different human arms, this paper will focus on meeting the requirements of upper limb rehabilitation in terms of ROM and DOF.

It remains an open issue to assess how many DOF are optimal for upper limb rehabilitation. The human arm is kinematically redundant and it has 7 degrees of freedom (DOF) with its shoulder, elbow, and wrist joints (excluding scapular motion), while positioning of the wrist in space and orientating the palm is a task that requires only 6 DOF. Many researches indicate that a therapy focusing on activities of daily living (ADL) has more positive effects on neuromuscular function and rehabilitation [11]. Considering that the hand flexion/extension and radial/ulnar deviation were relatively small during most representative daily functional tasks extensively studied in, the DOF of flexion/extension and radial/ulnar deviation of wrist were neglected in our kinematic model. Thus, the wrist was treated as the end point of the kinematic chain. The elbow joint was considered to be a two DOF hinge joint, i.e. flexion/extension and pronation/supination, and the shoulder joint was considered to be a three DOF hinge joint, i.e. flexion/extension, abduction/adduction and interior/exterior. Requirements for the ROM are shown in table 1.

Table 1. ROM of Shoulder and Elbow Joints

Axis	ROM
1 (shoulder flexion/extension)	-180° to 50°
2 (shoulder abduction/adduction)	-45° to 180°
3 (shoulder interior-exterior)	-90° to 90°
4 (elbow flexion/extension)	-150° to 0°
5 (elbow pronation/supination)	-90° to 90°

For the robot arms, DEREROB is a dual-arm robot system imitating the therapist with two attachments to the upper and lower arm of the patient. To move the affected arm in 3D space, 6 DOF are needed at least, with 3 DOF for positioning and 3 DOF for orientation. There is a trend of developing high DOF rehabilitation robots because high number of DOF allows a wide variety of movements. However, it can lead to the robot more complex and inconvenient. So the number of DOF

should be determined according to the actual condition and find a balance between the rehabilitation effects and treatment costs. By comprehensive consideration, each robot arm of DEREROB has 6 DOF, consisting of a 3 DOF spherical wrist and a 3DOF anthropomorphic arm.

The kinematic model of DEREROB was set up by using the Denavit Hartenberg (D-H) method [12], which allows the construction of the direct kinematics function by composition of the individual coordinate transformations expressed by equation (1) into one homogeneous transformation matrix as in equation (2).

$$A_i^{i-1} = Rot_z(\theta_i)Trans_z(d_i)Trans_x(a_i)Rot_x(\alpha_i)$$

$$= \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & a_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & a_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$T_n^0 = A_1^0(q_1)A_2^1(q_2) \cdots A_n^{n-1}(q_n)$$

$$= \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

where $[n_x \ n_y \ n_z]^T$, $[o_x \ o_y \ o_z]^T$ and $[a_x \ a_y \ a_z]^T$ respectively represent the normal, orientation and approach vectors. $[p_x \ p_y \ p_z]^T$ represents position vectors of the end coordinate in robot base along the x axis, y axis and z axis.

Since two robot arms of DEREROB are symmetrical, one robot arm was taken as an example to perform the kinematic analysis, and the D-H parameters for the kinematics are specified in Table 2.

Table 2. D-H parameters for one robot arm of DEREROB

Link	θ_i	d_i	a_i	α_i
1	θ_1	d_1	0	90°
2	θ_2	0	a_2	0
3	θ_3	0	0	90°
4	θ_4	d_4	0	-90°
5	θ_5	0	0	90°
6	θ_6	d_6	0	0

According to equation (1), the homogeneous transformation matrices for the single joints can be obtained. Then, the direct kinematics function can be computed based on equation (2) and the position and orientation of the end-effector frame are gained as follows:

$$p_6^0 = \begin{bmatrix} a_2c_1c_2 + d_4c_1s_{23} + d_6(c_1(c_{23}c_4s_5 + s_{23}c_5) + s_1s_4s_5) \\ a_2s_1c_2 + d_4s_1s_{23} + d_6(s_1(c_{23}c_4s_5 + s_{23}c_5) - c_1s_4s_5) \\ d_1 + a_2s_2 - d_4c_{23} + d_6(s_{23}c_4s_5 - c_{23}c_5) \end{bmatrix} \quad (3)$$

and

$$n_6^0 = \begin{bmatrix} c_1(c_{23}(c_4c_5c_6 - s_4s_6) - s_{23}s_5s_6) + s_1(s_4c_5c_6 + c_4s_6) \\ s_1(c_{23}(c_4c_5c_6 - s_4s_6) - s_{23}s_5s_6) - c_1(s_4c_5c_6 + c_4s_6) \\ s_{23}(c_4c_5c_6 - s_4s_6) + c_{23}s_5c_6 \end{bmatrix} \quad (4)$$

$$o_6^0 = \begin{bmatrix} c_1(-c_{23}(c_4c_5s_6 + s_4c_6) + s_{23}s_5s_6) + s_1(-s_4c_5s_6 + c_4c_6) \\ s_1(-c_{23}(c_4c_5s_6 + s_4c_6) + s_{23}s_5s_6) - c_1(-s_4c_5s_6 + c_4c_6) \\ -s_{23}(c_4c_5s_6 + s_4c_6) - c_{23}s_5s_6 \end{bmatrix} \quad (5)$$

$$a_6^0 = \begin{bmatrix} c_1(c_{23}(c_4s_5 + s_{23}c_5) + s_1s_4s_5) \\ s_1(c_{23}c_4s_5 + s_{23}c_5) - c_1s_4s_5 \\ s_{23}c_4s_5 - c_{23}c_5 \end{bmatrix} \quad (6)$$

Here, 's' and 'c' denote sine and cosine functions respectively. The notation $s_{i...j}, c_{i...j}$ denote respectively $\sin(q_i + \dots + q_j), \cos(q_i + \dots + q_j)$.

The direct kinematics equations of robot arm were computed and simulated by MATLAB to verify the correctness of the kinematics analysis. By substitution of the initial values, $\theta_1 = \theta_2 = \theta_3 = \theta_4 = \theta_5 = \theta_6 = 0$, into the direct kinematic model, the position and orientation of the robot arm can be obtained as shown in Figure 1, which is coincidence with its initial status.

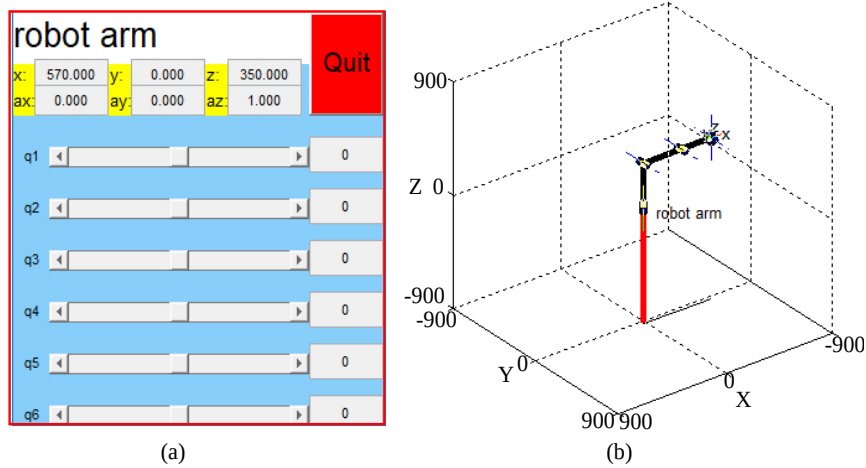


Figure 1. A Simulation Model of DEREROB. (a) Parameter Setting.
(b) Three-dimensional diagram of one robot arm of DEREROB

3. Simulation

3.1. Workspace Simulation

The workspace of a robot is considered of great interest from theoretical and practical viewpoint, being a basic tool for kinematic evaluation and dimensional design. Many methods working on robot workspace have been proposed, Monte-Carlo method [13] was chosen to use in this paper because of its accurate and efficient.

Based on the kinematics model of the DEREROB, the reachable workspace can be easily generated by using Monte-Carlo method as follows:

1. Determine variation ranges of the variables.

As for the robot arm of DEREROB, the position of its end-effector depends on variables $\{\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6\}$. And θ_i is characterized by the manipulator geometry and the mechanical joint limits. Thus $\theta_i^{min} \leq \theta_i \leq \theta_i^{max}$ can be acquired, here θ_i^{min} and θ_i^{max} are the minimize and maximum value of $\theta_i (i = 1, 2, \dots, 6)$ respectively.

2. Sample θ_i in $[\theta_i^{min}, \theta_i^{max}]$ randomly by the equation

$$\theta_i = \theta_i^{min} + (\theta_i^{max} - \theta_i^{min}) * RAND() \quad (7)$$

Here, using the Rand function to generate a random value as a variable step-length, that is, $(\theta_i^{max} - \theta_i^{min}) * RAND()$.

3. Generate a point $P = [p_x \ p_y \ p_z]^T$ for each value of these variables.

By substitution of the values $\{\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6\}$ into equation (3), a point $P = [p_x \ p_y \ p_z]^T$ for a set of values of the variables can be obtained. And workspace of the DEREROB is the set of all points generated by this method.

The workspace of the DEREROB has simulated by using MATLAB and the results are shown in Figure 2. Here the blue region displays the ROM of the human arm while the pink region displays the ROM of the DEREROB. It's obvious that the DEREROB have a larger range of motion and contains the whole moving range of human arm, which proves that the kinematic design of the DEREROB could meet the requirement of assisting patient's arm with rehabilitation exercise in space.

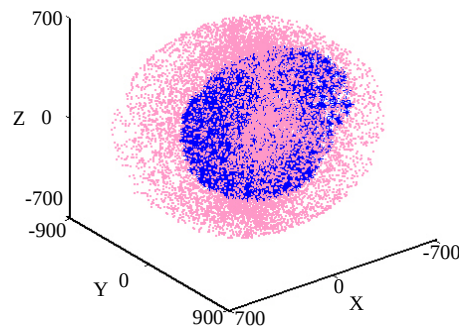


Figure 2. Working space of the human arm and the DEREROB.

3.2. Kinematics Simulation

Based on the analyses mentioned above, the DEREROB has been designed and modeled by using SolidWorks, as shown in Figure 3. Each robot arm of the DEREROB consists 6 DOF, which can meet the requirement of position/orientation in 3D space. With two attachments to the patients upper and lower arms, the DEREROB can provide a safe and intensive motor therapy to stroke patients, just like under the assistance of their therapists.

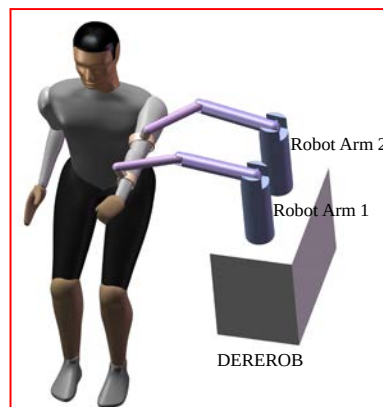


Figure 3. Three-dimensional model of the DEREROB

To verify the effectiveness of the DEREROB, motion simulation of the whole device was drawn by utilizing the software ADAMS. Two representative tasks, which are frequently performed in daily living, were selected to evaluate the feasibility of the DEREROB: drinking and touching the contra lateral shoulder. These two task-oriented robot-assistance were performed and the angular displacement curves of Joints of the DEREROB are shown in Figure 4 and Figure 5, respectively. As shown, the angular displacement curve of each joint is smooth and successive, which indicates that the operation of the DEREROB is stable and reliable. In other words, these tasks can be completed through the dual-arm robot cooperative movement. Thus, the DEREROB can commendably assist hemiplegic patients with rehabilitation training.

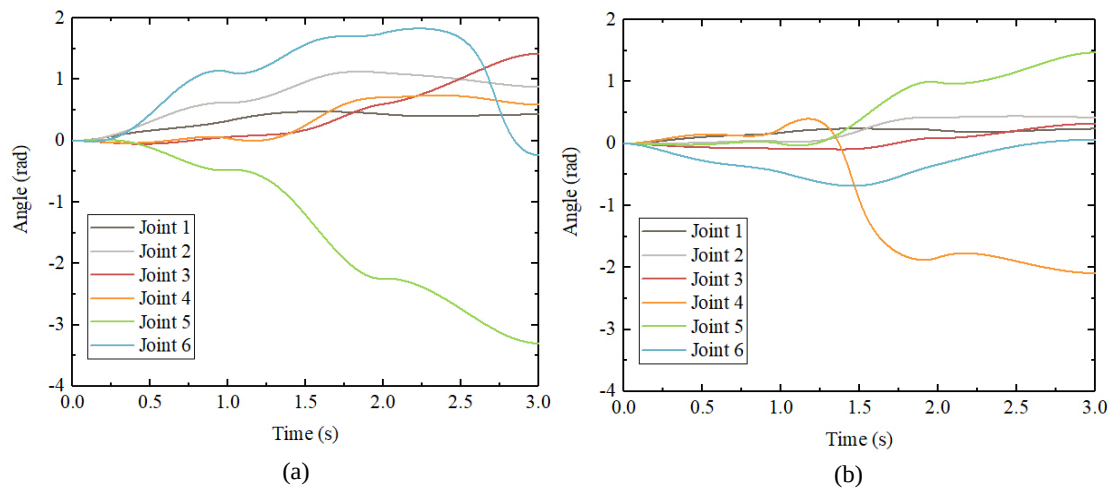


Figure 4. The angular displacement curves of Joints of the DEREROB corresponding to drinking water from a cup placed on the table. (a) shows the angular displacement curves of Joint i , ($i=1,2, \dots,6$) of the Robot Arm 1, respectively. And (b) shows the angular displacement curves of Joint i , ($i=1,2, \dots,6$) of the Robot Arm 2, respectively.

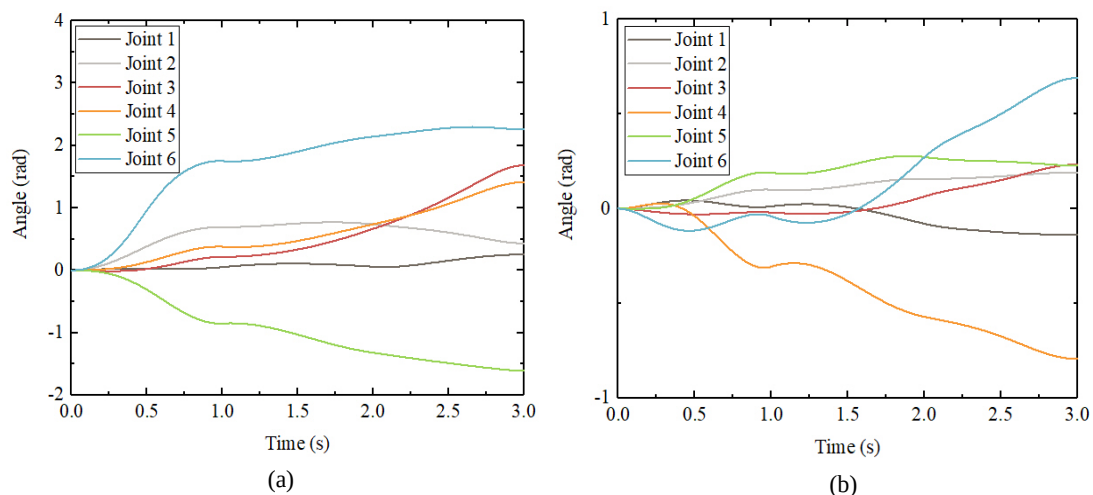


Figure 5. The angular displacement curves of Joints of the DEREROB corresponding to the touching contra lateral shoulder. (a) shows the angular displacement curves of Joint i , ($i=1,2, \dots,6$) of the Robot Arm 1, respectively. And (b) shows the angular displacement curves of Joint i , ($i=1,2, \dots,6$) of the Robot Arm 2, respectively.

4. Conclusion

This paper introduces a brand new robot called DEREROB for assisting hemiplegic upper limb with rehabilitation training. Kinematics and workspace simulation of the device is completed and simulation results show that indicates the feasibility and effectiveness of the DEREROB to move patient's arm in 3D space. The DEREROB prototype will be manufactured and tested for hemiplegic patients. In the future, machine vision and virtual reality will be introduced to enhance the accuracy and improve the training enjoyment.

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