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Optimizing method of mechanism angle of upper limb rehabilitation robot at glenohumeral joint

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ABSTRACT

At present, there are seventy million stroke patients in China and annual death toll of stroke is 1 million 650 thousand people. The survivors about 75% become disabled persons and lose the ability to move. To address this issue, a kind of rehabilitation exoskeleton robot called YANARM is proposed which for training of shoulder complex. This paper, a kind of method for optimizing the angle parameters of series dynamic axes under given workspace conditions is presented. The forward and inverse kinematics solutions of glenohumeral mechanism are solved based on the exponential product formula (POE) and the Paden-Kahan sub-problem. The range of joint rotation angle can be inversely solved according to the end of the arm position at the borderline of the workspace. A curve between the angle and the CP which equal mean variance of joint rotation range plus sum of all joint rotation ranges is solved. The mechanism angle of glenohumeral joint is optimized by this method.

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1. Introduction

Post-stroke motor dysfunction is a major problem faced by neurologists. The rehabilitation of the upper limbs of stroke patients has important clinical significance, and the upper limb rehabilitation robot is an important means to solve this problem [1].
Research on upper limb rehabilitation robot began in 1970s [2]. Most of the existing upper limb rehabilitation robots have six or less degrees of freedom. The representative product is the Armeo Power developed by HOCOMA Company [3], which is currently the most widely used upper limb rehabilitation robot in clinical practice. Most of the robots are large to maximize the range of motion of patients 'upper limbs in the rehabilitation process, which affects the selection of motor power to be larger. To optimize the layout of motor in glenohumeral joint and maximize the power-weight ratio of the robot, it is of great significance to the rehabilitation training of shoulder joint by using smaller motor. At present, most rehabilitation robots in the world have orthogonal motor axes in shoulder joint. For example, LIMPACT, an upper limb rehabilitation robot developed by Twente University in the Netherlands [4]. Intelli-Arm, an upper limb rehabilitation robot developed by North-western University [5], and a two-arm rehabilitation robot system developed by Pinole from Italy. Meanwhile a few of robots have considered axis angle of glenohumeral joint motor in design [6]. A MEDARM has been designed by Queen's University of Canada whose shoulder joint structure with small volume [7], however it is very complicated to maintenance and processing for using the rope wheel be the driver. A 7-DOF two-arm rehabilitation robot EXO-UL7 was designed by Washington University, as in [8].

The dynamic considerations were taken into account to reduce the power consumption of the motor, and the trajectory planning and coordinated control of the two arms were carried out. The University of Texas has developed a two-arm rehabilitation robot, Harmony, as shown in Figure 1 from [9]. The axis angle selection of the three motors for the glenohumeral joint ensures that the whole device can still achieve a workspace compatible with the range of human motion in a smaller volume.

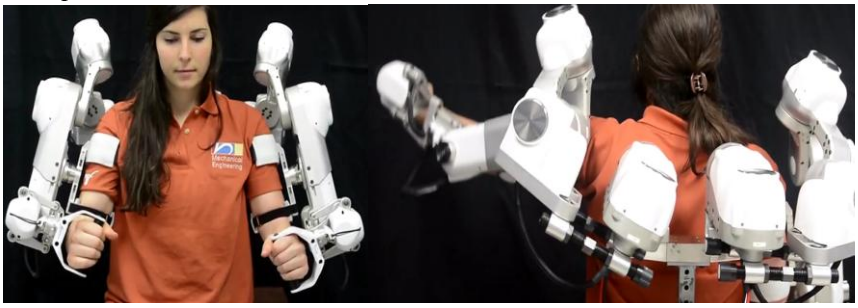

Figure 1. Harmony robot

In view of the spherical workspace of 3R series spherical mechanism, this paper presents a method to optimize the angle parameters of series dynamic axes under given workspace conditions.

2. Configura Design

2.1. The structure and movement mode of shoulder joint

As is known to all, that the human shoulder joint is equivalent to a spherical pair, and the arm mechanism is equivalent to a spherical mechanism which can be selected mainly by a parallel 6R spherical mechanism and a serial 3R spherical mechanism [10], [11]. The working space of the former one is small, and the branches are more likely to interfere with the human body, moreover it requires extremely high and assembly processes to make the three rotating shaft spaces to one point. The other has simple structure and is easy to motion. Combining various factors, this paper chooses serial 3R spherical mechanism as the arm mechanism.
The structure of the mechanism is shown in Figure 2: the shaft $\$_1$, $\$_2$, and $\$_3$ form the upper arm, and the angles between the any two axes of link is α; the axis $\$_4$ controls the motion of the elbow joint, the axis $\$_5$ controls the axial rotation of the upper arm, and the axis $\$_6$ controls the motion of the wrist.

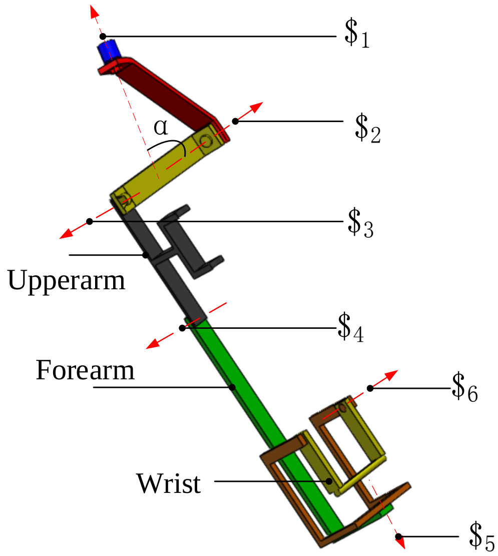

Figure 2. 3D model of the structure configuration

The schematic diagram of the mechanism is as shown in Fig.3. The reference coordinate system S and the tool coordinate system T (fixed at the end of the upper arm mechanism) are established, and the coordinate system J (fixed at the rotation centre of the right shoulder joint coincide with S, and the human body faces the negative direction of the Y axis).The three joint axes $\$_1$、 $\$_2$、 $\$_3$ intersect at a point S, and the axis $\$_1$ is fixed. The angles between the any two axes of link is α, the length of the upper arm is L, and the joint angle is θ_1、θ_2、θ_3 .

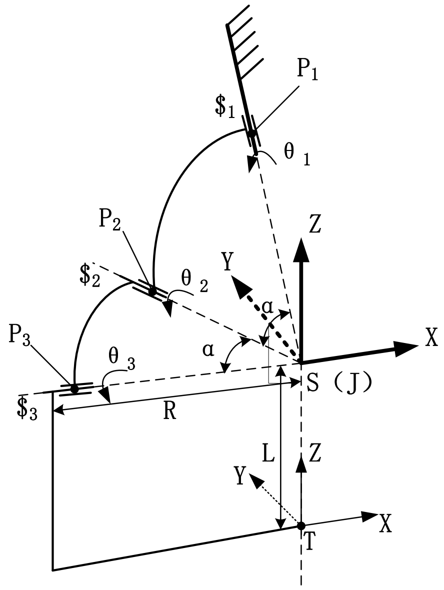

Figure 3. Schematic diagram of the upper arm mechanism

There are many algorithms in mechanism optimization, as in [12], [13], and [14], in this paper POE and the Paden-Kahan sub-problem used to solve the problem.

When $\boldsymbol{\theta}_{db}=\begin{bmatrix}\theta_1 & \theta_2 & \theta_3\end{bmatrix}^T=\begin{bmatrix}0 & 0 & 0\end{bmatrix}^T$, corresponding to the configuration of the upper arm mechanism shown in Figure 6. When $\boldsymbol{\theta}_{db}=\boldsymbol{0}$, the transformation of the reference coordinate system S and the tool coordinate system T is:

$$\boldsymbol{g}_{st}(\boldsymbol{0})=\begin{bmatrix}\boldsymbol{I} & \begin{bmatrix}0\\0\\-L\end{bmatrix}\\ 0 & 1\end{bmatrix} \tag{1}$$

$\boldsymbol{I}$ is a 3×3 unit array. The coordinates of each motion spin are:

$$\begin{aligned}\boldsymbol{\xi}_1&=\begin{pmatrix}c_\alpha^2 & -s_\alpha c_\alpha & -s_\alpha & 0 & 0 & 0\end{pmatrix}^T\\ \boldsymbol{\xi}_2&=\begin{pmatrix}c_\alpha & -s_\alpha & 0 & 0 & 0 & 0\end{pmatrix}^T\\ \boldsymbol{\xi}_3&=\begin{pmatrix}1 & 0 & 0 & 0 & 0 & 0\end{pmatrix}^T\end{aligned} \tag{2}$$

The forward kinematics map has the following form:

$$\begin{aligned}\boldsymbol{g}_{st}(\boldsymbol{\theta}_{db})&=e^{\hat{\xi}_1\theta_1}e^{\hat{\xi}_2\theta_2}e^{\hat{\xi}_3\theta_3}\boldsymbol{g}_{st}(\boldsymbol{0})\\ &=\begin{bmatrix}\boldsymbol{R}(\boldsymbol{\theta}_{db}) & \boldsymbol{P}(\boldsymbol{\theta}_{db})\\ 0 & 1\end{bmatrix}\end{aligned} \tag{3}$$

2.2. Inverse kinematics

Let Eqs. (3) be equal to $\boldsymbol{g}_d$:

$$\boldsymbol{g}_{st}\left(\boldsymbol{\theta}_{db}\right)=e^{\hat{\xi}_1\theta_1}e^{\hat{\xi}_2\theta_2}e^{\hat{\xi}_3\theta_3}\boldsymbol{g}_{st}\left(\boldsymbol{0}\right)=\boldsymbol{g}_d \tag{4}$$

In Eqs. (4), $\boldsymbol{g}_d \in SE(3)$ is the desired shape of the tool coordinate system T, also the desired shape of the upper arm. Eqs. (4) left multiply $\boldsymbol{g}_{st}^{-1}\left(\boldsymbol{0}\right)$ to get exponential mapping

$$e^{\hat{\xi}_1\theta_1}e^{\hat{\xi}_2\theta_2}e^{\hat{\xi}_3\theta_3}=\boldsymbol{g}_d\boldsymbol{g}_{st}^{-1}\left(\boldsymbol{0}\right)=\boldsymbol{G}_1 \tag{5}$$

First step (solving θ_1 and θ_2): applying both sides of Eqs. (5) to the point $\boldsymbol{P}_3 \in R(3)$ on axis $\$_3$ (but the point is not on the axis $\$_1$ and $\$_2$).Because of $e^{\hat{\xi}_3\theta_3}\boldsymbol{P}_3=\boldsymbol{P}_3$, so:

$$e^{\hat{\xi}_1\theta_1}e^{\hat{\xi}_2\theta_2}\boldsymbol{P}_3=\boldsymbol{G}_1\boldsymbol{P}_3 \tag{6}$$

The above equation conforms to the form of the Paden-kahan sub-question 2. In Eqs. (6), $\boldsymbol{P}=\boldsymbol{P}_3$ $\boldsymbol{Q}=\boldsymbol{G}_1\boldsymbol{P}_3$, θ_1 and θ_2 can be solved.

Second step (solving θ_3): since θ_1 and θ_2 are known, Eqs. (5) can be transformed into:

$$e^{\hat{\xi}_3\theta_3}=e^{-\hat{\xi}_2\theta_2}e^{-\hat{\xi}_1\theta_1}\boldsymbol{G}_1 \tag{7}$$

Applying both sides of Eqs. (7) to the point $\boldsymbol{P}_2 \in R(3)$ on axis $\$_2$ (but not at axis $\$_1$ and $\$_3$):

$$e^{\hat{\xi}_3\theta_3}\boldsymbol{P}_2=e^{-\hat{\xi}_2\theta_2}e^{-\hat{\xi}_1\theta_1}\boldsymbol{G}_1\boldsymbol{P}_2 \tag{8}$$

The above equation conforms to the form of the Paden-kahan sub-question 1. In Eqs.(8), $\boldsymbol{P}=\boldsymbol{P}_2$ $\boldsymbol{Q}=e^{-\hat{\xi}_2\theta_2}e^{-\hat{\xi}_1\theta_1}\boldsymbol{G}_1\boldsymbol{P}_2$, θ_3 can be solved.

3. Mechanism Parameter Optinization

In order to get more rang of motion (ROM) of shoulder, it is necessary to optimize the mechanism angle. In [15], Luige's research on robotic haptic sense points out the direction for the follow-up study of this paper.

Since S and J coincide, the representation of the four extreme poses of the human body in the coordinate system J is the same as the pose of the tool coordinate system T under the reference coordinate system S:

Substituting $\boldsymbol{g}_{dA}$, $\boldsymbol{g}_{dB}$, $\boldsymbol{g}_{dC}$, and $\boldsymbol{g}_{dD}$ into Eqs. (4) respectively, the value of θ_1, θ_2, and θ_3 can be solved according to the inverse solution algorithm. Each extreme pose can solve two sets of inverse solutions, and each group of inverse solutions corresponding to each of the four extreme positions can get a combination. There are 16 cases, for each case can get a range of θ_1, θ_2, and θ_3 values.

Define $AR_{op}=fw_1+fw_2+fw_3+st_{123}$ as the angle indicator. When AR_{op} is minimum, the total rotation range of the three rotation pairs is small, and the distribution on the three rotation pairs is relatively uniform.

When AR_{op} is the smallest, the corresponding combination is the optimal combination, and the range of values of the three angles corresponding to the combination is selected. Where fw_i is the range of values for θ_i and st_{123} is the mean square of the range of values for the three angles. The relationship between α and AR_{op} is shown in Figure 4.

Known from Figure 4, $AR_{op}=433^{\circ}$ is the minimum value when $\alpha=72^{\circ}$. When $\alpha=72^{\circ}$, it is the optimal solution.

When $\alpha=72^{\circ}$ and AR_{op} smallest corresponding arrangement, obtain $\theta_1 \in \left(-58,123\right)$, $\theta_2 \in \left(-142,15\right)$, $\theta_3 \in \left(-96,0\right)$. Substituting them into the positive solution equation, we got the positional relationship between the arc path and the spherical area of the point (P_2 and P_3) , and the human body area , as shown in Fig. 5.

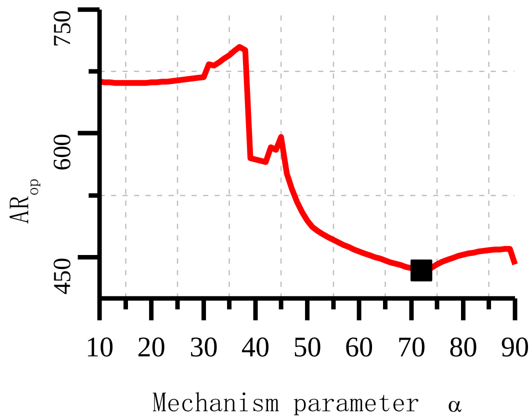

Figure 4. Relationship between α and AR_{op}

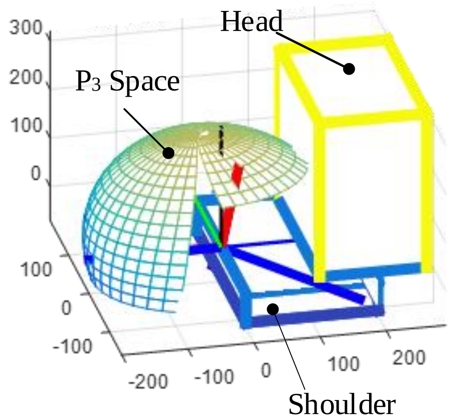

Figure 5. Intervention between the mechanism and human body

4. Conclusion

By defining the angle index, the angle of the mechanism linkage is globally optimized, so that the total rotation range of the three rotation pairs is small, and the distribution on the three rotation pairs is relatively uniform.

By defining the distance parameter JL, performing global optimization from the two dimensions β_1 and β_2. The obtained pose parameters can effectively avoid the interference between the mechanism and the human body.

The internal and external rotation degrees of the end link are artificially fixed, that is, the same internal and external rotation angles are used for multiple extreme positions. When different internal and external rotation angles are taken, different optimization results are obtained, and the subsequent relationship will be further studied.

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