Study on the Man-machine Motion Planning of Rigid-flexible Hybrid Rehabilitation Robot

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Abstract. At present, the general lower limb rehabilitation training robot is only achieving motion training of lower limbs flexion and extension. The lower limb rehabilitation training robot was conceived that included the rigid mobile vice-flexible driving system, which realized the lower limbs movement of adduction or abduction and Internal or external rotation at the same time, and its aimed to research the robot’s structure and motion planning. The kinematics model of the robot was analyzed by the influence coefficient method. According to the rehabilitation training of man-machine cooperation relations, kinematic simulation analysis was carried out. The simulation analysis of the state of flexible cable movement was conducted by the trajectory of the training program, which provided the foundation for the system dynamics modeling and the selection of the driving element.

Introduction

With the fast pace of modern life and lifestyle changes, from the treatment of stroke and infantile paralysis patients to muscle rehabilitation, besides early surgical treatment, recovery training is also very important in the later stage[1]. In recent years, it has gradually been recognized by the society that the rehabilitation training methods used to replace the traditional physical exercise therapy [2]. According to the functional of the lower limb rehabilitation training robot, it divided into the multifunctional lower limb rehabilitation robot and local functional rehabilitation robot. The former robot aims at rehabilitation training for the whole lower limbs, and the latter specifically aimed at a joint or part of the lower limb and targeted implementation of rehabilitation training. The rigid mechanism of robot structure often appeared in the rehabilitation training of lower limbs. The Free University in Germany developed a lower limb rehabilitation robot MGT [3], its gait mechanism adopted a crank rocker mechanism, only 1 degrees of freedom, single function, so it can’t achieve complex motion. Swiss Federal Institute of technology in Zurich developed the Lokomat lower limb rehabilitation robot [4], with 4 rotational degrees of freedom, which wearing device to drive the legs of the trainers to achieve gait movement, but the overall body was complex and expensive. The research of this aspect in China also made some progress, Harbin Engineering University developed the equipment using a parallel mechanism control pedal to achieve the stepping [5], which can meet the different needs of various movement of the lower extremity, but the mechanism is relatively large. Shanghai University, Zhejiang University and other units developed a device of lower extremity dermatoskeleton [6-7], it achieved motion by electric cylinder linear drive to achieve the rotation to control the movement of the joints of the lower limbs. Above-mentioned, the main research of the rehabilitation robot is the human gait movement, and the training of muscular strength of the medial thigh muscle group is not obvious. In order to meet the needs of the rehabilitation training path, this paper proposes a kind of rigid-flexible hybrid adduction and abduction rehabilitation robot which special help patients with medial thigh muscle group exercise rehabilitation training. Meanwhile, the robot mechanism and trajectory planning are analyzed and the results prove the feasibility and effectiveness of the robot.
Robot Kinematics Analysis

According to the implementation of lower limb adduction and abduction of training forms and the specific location of the lower limb control point, then referring the lower limb of the human body kinematics model, the motion form of the control point can be clearly defined, so as to determine the robot's mechanism form. This paper presents a rigid-flexible hybrid robot, and robot system is composed of 4 groups of rigid-flexible hybrid chains and pedal rigid-flexible hybrid chain mechanism consists of a fixed linear slide on the frame and flexible cable. Linear slide is used to change the position of flexible cable wheel and the pedal is pulled by 4 cable. The other end of the rope is respectively connected by the capstan wheel and driven winch DC torque motor in Figure 1.

![Figure 1. Robot training model.](image)

Pedal Kinematics Modeling

Referred to a kinematic model of six degree of freedom of the human body’s lower limb [8]and according to the trajectory of the rehabilitation process of lower limb control points with the joint angle changing, the position solution of the pedal center point in the abduction and adduction movement is solved. Relative to the basic coordinate system of the robot, the position of the pedal center point is changing with the change of the joint angle:

\[ P = {}^aT_\rho \cdot \Theta + O \]  

Where in: \( P \), The coordinate of the pedal center point in the world coordinate system; \( \Theta \), The angle of lower limb joint in human body coordinate system; \( O \), The position of the origin of the human body coordinate system in the world coordinate system; \( {}^aT_\rho \), The coordinate transformation matrix of the D-H model of the human lower limb.

Because the joint in the D-H model of the human lower limb is a rotary joint, according to the method of solving the singular transformation matrix, The velocity mapping relationship of human lower limb control points of the pedal center point is derived. That is:

\[ \dot{P} = {}^aT_\rho \cdot \dot{\Theta} + {}^aT_\rho \cdot \dot{\Theta} \]  

According to \( {}^0T_\rho = {}_0T_\rho (q_1, q_2, \cdots, q_n) \) and \( {}^0T = {}^i_0T^{-1}T, (Q_0T = I) \), The following recurrence formula can be obtained:

\[ \begin{align*}
{}^0T_i & = {}^i_0T^{-1}T + {}^0T^{-1}T + {}^i_0T \left( \frac{d}{dq_i} {}^0T_i^{-1}T \right) \dot{q}_i = {}^i_0T^{-1}T + {}^0T^{-1}T Q_0 \dot{q}_i = {}^i_0T^{-1}T + {}^0T Q_0 \dot{q}_i \\
\end{align*} \]

Among, (\( {}^{\cdots}_{\rho}a \dot{q} = O \)).

The recurrence formula can be further solved as follows:
\[ \dot{T}_i = \dot{\Theta}_i T + \dot{i}_i T + \dot{T}_Q \dot{i}_i + \dot{T}_Q \dot{i}_i = \dot{\Theta}_i T + \dot{i}_i T + \dot{T}_Q \dot{i}_i + \dot{T}_Q \dot{i}_i \]

Among, \( \dot{T}_Q = 0 \).

So the acceleration of the pedal center point \( \dot{P} \) can be obtained.

**Flexible Cable Kinematics Modeling**

The rigid-flexible hybrid robot configuration (Figure 1) shows that the robot flexible cable’s projection in X plane and Y plane as shown in Figure 2 the posture change rule of the pedal center point is obtained by man-machine training trajectory analysis, then the coordinate of the traction point \( \begin{bmatrix} P_{ix}, P_{iy}, P_{iz} \end{bmatrix} \) of the pedal can be obtained:

\[
\begin{bmatrix} P_{ix}, P_{iy}, P_{iz} \end{bmatrix}^T = R \cdot r_i + \begin{bmatrix} P_{ix}, P_{iy}, P_{iz} \end{bmatrix}^T
\]

Among them, \( R \) is the transformation matrix of the pedal coordinate system \( P_x, y, z, P \), which is relative to the base coordinate system \( o, x, y, z, \), \( r_i = PP_i \). The direction vector of point \( P_i \) in the pedal coordinate system is relative to the origin \( P \) of the coordinate system.

![Rope distribution master view](image)

![Rope distribution top view](image)

Figure 2. The distribution of flexible cable.

Therefore, when the wheel point \( B \) and \( P \) relative to the fixed coordinate system coordinates are known, there is \( L_i = PP_i \), the length \( l_i \) of each rope can be obtained:

\[
l_i = \sqrt{(B_{ix} - P_{ix})^2 + (B_{iy} - P_{iy})^2 + (B_{iz} - P_{iz})^2}
\]

The derivation of equation \( l_i = L_i \) to get rope speed, that is:

\[
\dot{l}_i = (L_i / l_i) \cdot v_{PB} = u_i \cdot v_{PB}
\]

Among, \( u_i = \begin{bmatrix} P_{ix} - B_{ix}, P_{iy} - B_{iy}, P_{iz} - B_{iz} \end{bmatrix} / \|PB\| \) represents the unit direction vector of the rope \( i \); \( v_{PB} \) indicates the speed of the rope \( i \), \( v_{PB} = v_P - v_B \).

When the speed \( \dot{P} = \begin{bmatrix} \omega_x, \omega_y, \omega_z, v_x, v_y, v_z \end{bmatrix}^T \) of the center of the pedal is known, \( v_P \) can be expressed as

\[
v_P = G_P^B \cdot \dot{P}
\]

Among, \( G_P^B \) represents the speed transformation matrix between the center point \( P \) of the pedal and the connecting point of each rope. That is:

\[
G_P^B = [i \times r_i, j \times r_j, k \times r_k, i, j, k] \in R^{3 \times 6}
\]
Among, $x$ axis direction unit vector for $i$, $i = [1,0,0]^T$; $y$ axis direction unit vector for $j$, $j = [0,1,0]^T$; $z$ axis direction unit vector for $k$, $k = [0,0,1]^T$;

This can be pushed:

$$\ddot{l}_i = u_i \cdot G_p^i \cdot \ddot{P} - u_i \cdot v_{B_i} = J_i \cdot \dot{P} - u_i \cdot v_{B_i}$$  \hspace{1cm} (10)$$

Among, $J_i$ is the first-order influence coefficient of the rope $i$ to the moving platform, $J_i = u_i \cdot G_p^i$. That is $J = [J_1, J_2, J_3, J_4]$.

The motion state of the rope can lay the foundation for dynamic analysis and selection of the drive motor[9].

**Simulation Analysis**

In the lower limb of the human body model, rehabilitation training mode is set, which is a special passive adduction and abduction for patients, then this mode corresponds to the lower limb function of the joint angle is as follows:

$$\begin{align*}
\theta_1 &= -45\sin(2.7t-0.34)-15;
\theta_2 &= -10\sin(2.7t) \\
\theta_3 &= 20;
\theta_4 &= 0 \\
\theta_5 &= 45;
\theta_6 &= -10\sin(2.7t)
\end{align*}$$  \hspace{1cm} (11)

Where in, $\theta_1$ lower extremity hip adduction and abduction angle, degree; $\theta_2$ internal rotation and external rotation angle of hip joint in lower limbs, degree; $\theta_3$ lower limb hip flexion and extension angle, degree; $\theta_4$ lower limb knee flexion and extension angle, degree; $\theta_5$ lower limb ankle flexion and extension angle, degree; $\theta_6$ lower limb ankle adduction and abduction angle, degree; $t$ lower limb training time, s.

By man-machine training trajectory analysis, Considering the motor function in patients with disorders of one complete lower limb adduction and abduction action is time-consuming in the rehabilitation process and taking into account the safety of patients, thus, rigid flexible hybrid robot (adduction and abduction) in the adduction and abduction movement is set up, which complete a set of training mode in frequency of 2.7HZ, and then the running state of the mobile platform center P in adduction and abduction training is simulated. Figure 6 shows the relationship between the speed of the moving platform center and the training time. Figure 7 shows the relationship between the acceleration of the moving platform center and the training time.

![Velocity variation law of the moving platform center.](image)
As can be seen from Figure 3, the center of the moving platform had the largest velocity (about \(-1500 \leftrightarrow 1500 \text{mm/s}\)) along the X axis, it had the middle velocity (about \(-1000 \leftrightarrow 1000 \text{mm/s}\)) along the Y axis and the minimum velocity (in \(\pm 10 \text{mm/s}\)) along the Z axis. From Figure 4, acceleration is similar to velocity on three axes (x y z) in the law changing, the center of the moving platform had the largest acceleration (about \(-4000 \leftrightarrow 4000 \text{mm/s}^2\)) along the X axis, and it had the centered acceleration (about \(-2000 \leftrightarrow 4000 \text{mm/s}^2\)) along the Y axis and the minimum velocity (in \(\pm 500 \text{mm/s}\)) along the Z axis. Compared to the motion law of point D movement in Figure 2 the correctness of model about the moving platform center speed and acceleration is verified, which laid the foundation for the next solving about rope length, velocity and acceleration.

**Summary**

Aiming at the general problem of lower limb rehabilitation training robot which is only doing flexion and extension movement training of lower limb, lower limb rehabilitation robot configuration is put up, which can also achieve lower limb exercise training of adduction or abduction and internal or external rotation. Referring to the human body kinematics model of the lower limb, the structure of lower limb rehabilitation robot is set up, which is the rigid-flexible hybrid model. According to the rigid-flexible hybrid structure of lower limb rehabilitation robot, the kinematic model of pedal is established at situation of fully considering the human lower limb movement track. Then mapping relation between joint movement of lower limb and pedal movement is obtained. Meanwhile, the kinematic model of rope traction is set up and the first-order and second-order influence coefficient matrix of system of rope traction is obtained. Those provide a foundation for the analysis of system dynamic. Based on training patterns of adduction or abduction and internal or external rotation and planning strategy of man-machine, the speed, acceleration of the pedal center point and length, speed and acceleration of rope are simulated and analyzed. Then the validity of the trajectory planning strategy of man-machine training is verified. Those laid the foundation for the next step of the robot controlling.

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**References**


