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Design and Research of the Wire – Driven Lumbar Parallel Rehabilitation Device

Ming-De GONG[a], and Xiang-Fei KONG[b]*
[1] School of Mechanical Science and Engineering, Jilin University, 130025 Changchun, China
[a]gmd@jlu.edu.cn, [b]kongxf14@mails.jlu.edu.cn
*Corresponding author: Xiang-Fei KONG

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Abstract. In this paper, a new type of wire-driven lumbar parallel rehabilitation device is designed based on the wire-driven parallel robot to realize the purpose of rehabilitation training the lumbar of the patient. On the basis of designing the mechanical structure, the kinematics of the device is analysed by Newton iteration method and the dynamic equation is solved. The kinematic trajectory is simulated according to the data of the lumbar of the rehabilitation patient. Using fuzzy sliding mode control, the controller is designed to output the force and movement needed in the rehabilitation process to ensure the normal function of the lumbar function.

Introduction

Wire-driven parallel robot is a new kind of robot, which uses wire as the transmission tool, one end connects the moving platform and the other end connects the driving motor, to make the platform move in the desired working space [1-3].

The wire-driven parallel robot has the characteristics of light weight, fixed driving unit, small inertia and flexible transmission that the wire-driven robot has. It also has the characteristics of high precision, large load/weight ratio, no error accumulation of mechanism and good rigidity that the parallel robot has. In this paper, a new type of wire-driven lumbar parallel rehabilitation device is designed based on the wire-driven parallel robot to realize the purpose of rehabilitation training of the waist of the patient [4-7].

The Design of the Wire-Driven Lumbar Parallel Rehabilitation Device

The Mechanical Structure of the Device

The wire-driven lumbar parallel rehabilitation device is composed of mobile driving mechanism, fixed driving mechanism, wire rehabilitation mechanism and frame. The structure of the lumbar parallel rehabilitation device is illustrated in figure 1.

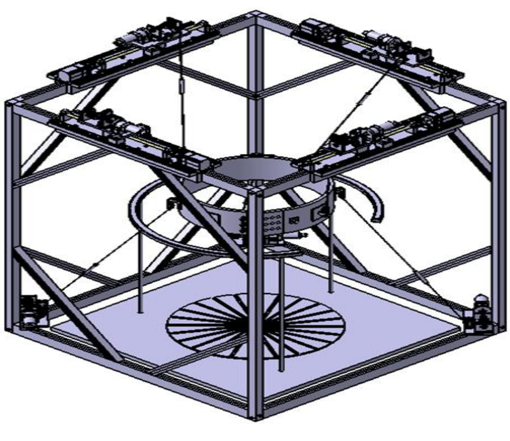

Figure 1. Wire-driven lumbar parallel rehabilitation device.

The axonometric diagram of the wire-driven lumbar parallel rehabilitation device is given below in figure 2. The mobile driving mechanism I, II, III and IV are sequentially arranged at the top of the frame. The fixed driving mechanism V, VI and VII are arranged on the fixed plate at the bottom of the frame. The wire rehabilitation mechanism VIII is arranged at the center of the frame IX through seven steel wire ropes. One end of the steel wire rope connects the driving mechanism and the other end of the steel wire rope connects the rehabilitation belt of the wire rehabilitation mechanism VIII.

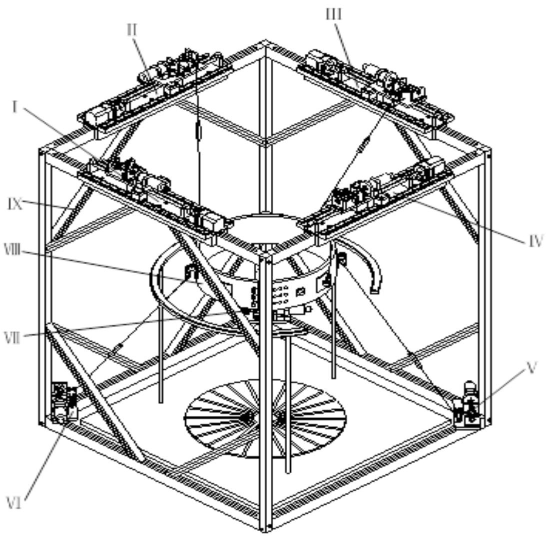

Figure 2. Axonometric diagram of the rehabilitation device.

The three-dimensional structure of mobile driving mechanism is illustrated in figure 3. The servo motor drives the winding unit through the ball screw mechanism on the sliding rail. The stepping motor in the winding unit realizes the purpose of winding the wire rope through the worm gear mechanism and the gear rack mechanism ensures that the guide wheel and the wire rope are in the same plane in the process of winding. This mechanism is designed to ensure the accuracy and smoothness of motion transmission.

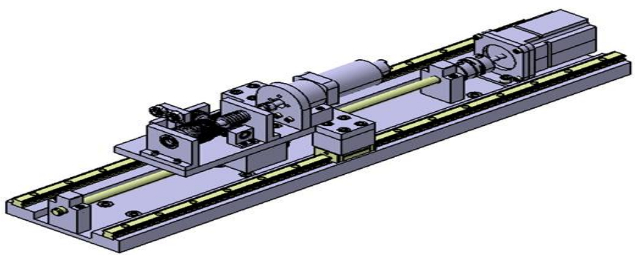

Figure 3. Structure of mobile driving mechanism.

The patient enters the rehabilitation belt from the armrest mouth and wears the belt in a comfortable position. Four mobile driving mechanisms and three fixed driving mechanisms first control the belt movement in Z direction and make the belt fit the patient's position of rehabilitation. Then the driving mechanisms apply force to bring the rope in a correct position and tension state. When the balance adjustment is completed, the relevant parameters will be entered to conduct the patient rehabilitation training. If the patient rehabilitation process is unexpected, simply press the brake button on the belt, the device will stop working to ensure the patient safety.

Kinematics Analysis

The three-dimensional coordinate diagram of the lumbar parallel rehabilitation device is given below in figure 4. The fixed coordinate system is defined as Oxyz, the local coordinate system is $Qx_Py_Pz_P$, the origin of the local coordinate system is the center of the rehabilitation belt. The positive direction of the x axis is the negative direction of the human sagittal axis, the positive direction of the y axis is the positive direction of the human coronal axis and the positive direction of the z axis is the positive direction of the human vertical axis. P_1, P_2, P_3, P_4, P_5, P_6 and P_7 are the seven connection points of the steel wire ropes and the belt respectively. The belt is pulled by seven ropes, and the other end of the ropes are respectively through the A_i(i=1, 2…7) connected to the winding device driven by the stepping motor.

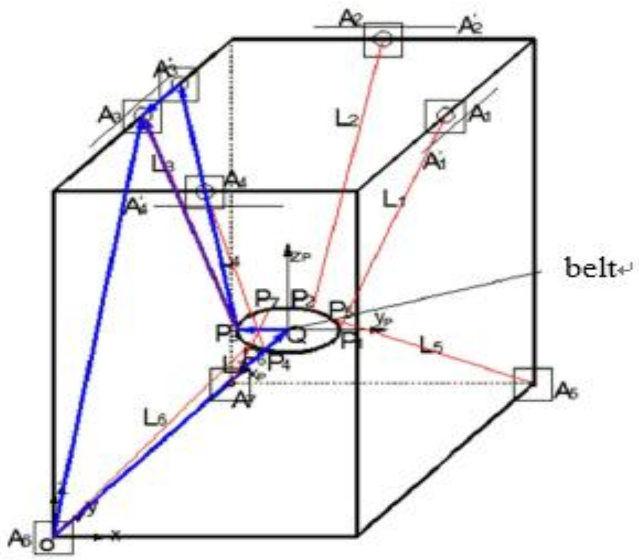

Figure 4. Coordinate of the rehabilitation device

$\overrightarrow{OP_i}$(i=1, 2…7) is the position vector of the point P_i in the fixed coordinate system, $\overrightarrow{L_i^{'}}=\overrightarrow{P_iA_i^{'}}$(i=1,2…7) is the driving wire vector, $\overrightarrow{A_i^{'}A_i}$(i=1,2…7) is the mobile driving wire vector, $\overrightarrow{QP_i}$(i=1,2…7) is the position vector of the point P_i in the local coordinate system, $\overrightarrow{OQ}$ is the position vector in the local coordinate system relative to the fixed coordinate system and $\overrightarrow{L_i}=\overrightarrow{P_iA_i}$(i=1,2…7) is the theoretical driving wire vector.

Inverse solution process: according to the closed vector quadrangle law and robotics coordinate transformation, formula can be obtained,

$$\overrightarrow{OA_i}=\overrightarrow{OQ}+{}^{O}_{Q}\mathbf{R}\overrightarrow{QP_i}+\overrightarrow{L_i} \tag{1}$$

$$\overrightarrow{L_i}=\overrightarrow{OA_i}-\overrightarrow{OQ}-{}^{O}_{Q}\mathbf{R}\overrightarrow{QP_i}\quad(i=1,2\ldots7) \tag{2}$$

In the equation (1) ${}^{O}_{Q}\mathbf{R}=\mathbf{R}(x,\alpha)\mathbf{R}(y,\beta)\mathbf{R}(z,\gamma)$ is the rotation matrix in the local coordinate system $Qx_Py_pz_P$ relative to the fixed coordinate system Oxyz, (α, β, γ) is the rotation angle in the local coordinate system relative to the fixed coordinate system.

$${}^{O}_{Q}\mathbf{R}=\begin{bmatrix} c\alpha c\beta c\gamma - s\alpha s\gamma & -c\alpha c\beta s\gamma - s\alpha c\gamma & c\alpha s\beta \\ s\alpha c\beta c\gamma + c\alpha s\gamma & -s\alpha c\beta s\gamma + c\alpha c\gamma & s\alpha s\beta \\ -s\beta c\gamma & s\beta s\gamma & c\beta \end{bmatrix}_{3\times3} \tag{3}$$

$$c=\cos \quad s=\sin \tag{4}$$

$$L_i=\left\|\overrightarrow{L_i}\right\| \quad (i=1,2\ldots7) \tag{5}$$

$\overrightarrow{L_i^{'}}=\overrightarrow{P_iA_i^{'}}$(i=1,2…7)is the actual driving wire vector:

$$\overrightarrow{L_i^{'}}=\overrightarrow{L_i}-\overrightarrow{A_i^{'}A_i} \quad (i=1,2\ldots7) \tag{6}$$

$$L_i^{'}=\left\|\overrightarrow{L_i^{'}}\right\| \quad (i=1,2\ldots7) \tag{7}$$

Positive solution process: Because of the complexity of the cable-driven parallel robot, its kinematic positive solution is a group of nonlinear equations, so it is difficult to solve the positive solution. Newton-Raphson iteration is usually used to obtain the rotation angle.

$$\overrightarrow{L_i}=\overrightarrow{L_i^{'}}+\overrightarrow{A_i^{'}A_i} \quad (i=1,2\ldots7) \tag{8}$$

$$F_i(\overrightarrow{X})=\left\|\overrightarrow{L_i}\right\|^2-L_i^2 \quad (i=1,2\ldots7) \tag{9}$$

$$\overrightarrow{X}_{k+1}=\overrightarrow{X}_k+\boldsymbol{\delta}\overrightarrow{X}_k \tag{10}$$

$$\mathbf{J}\,\boldsymbol{\delta}\overrightarrow{X}=-\mathbf{F}(\overrightarrow{X}) \tag{11}$$

$$\boldsymbol{\delta}\overrightarrow{X}_k=-\mathbf{J}^{+}\mathbf{F}(\overrightarrow{X}) \tag{12}$$

$\overrightarrow{X}$is the moving platform pose matrix, $\boldsymbol{\delta}\overrightarrow{X}_0$ is the incremental value of the pose, $F_i(\overrightarrow{X})$ is the deviation function of the i wire, $\mathbf{J}_i$is the matrix of the partial derivative of the position θ by $F_i(\overrightarrow{X})$. Guess the initial value of the pose, $\overrightarrow{X}_{\mathbf{0}}=[X_0 \quad Y_0 \quad Z_0 \quad \alpha_0 \quad \beta_0 \quad \gamma_0]^T$, solve its corresponding incremental value $\boldsymbol{\delta}\overrightarrow{X}_0$, and then repeat the solution until $\left\|\boldsymbol{\delta}\overrightarrow{X}_k\right\|<\xi$. Solution is an approximate positive solution of kinematics, where ξ is the iterative error tolerance.

Dynamics Analysis

Statistic model: the statistic model of the rehabilitation belt is given below in figure 5. It shows the force diagram of the rehabilitation belt. According to the equilibrium principle, the static equilibrium equation is established:

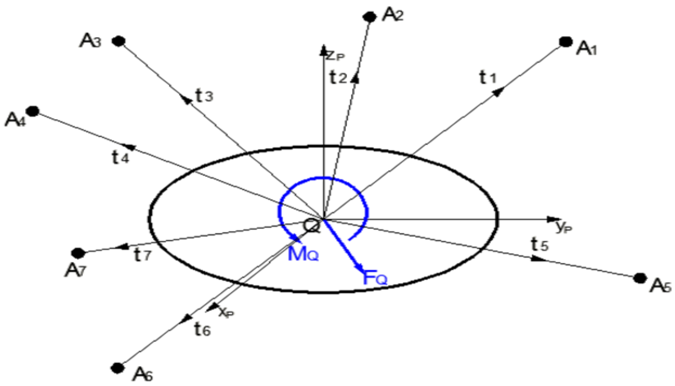

Figure 5. Statistic model of the rehabilitation belt

$$\begin{cases} \sum_{i=1}^{7} t_i+F_Q=0 \\ \sum_{i=1}^{7} {}^{O}_{Q}\mathbf{R}\overrightarrow{QP_i}\times t_i+M_Q=0 \end{cases} \tag{13}$$

$[F_Q \quad M_Q]^T$ is the external force of reference point Q on the belt. F_Q and M_Q is respectively the force and the torque applied by other objects other than the wire rope on the moving platform. T_i (i=1,2…7) is the value of the i driving rope pulling force.t_i (i=1,2…7) is the tension vector of the i driving rope.

$$t_i=-T_i\mathbf{U}_i \tag{14}$$

${}^{O}_{Q}\mathbf{R}=\mathbf{R}(x,\alpha)\mathbf{R}(y,\beta)\mathbf{R}(z,\gamma)$ is the rotation matrix in the local coordinate system $Qx_Py_Pz_P$ relative to the fixed coordinate system Oxyz .

$${}^{O}_{Q}\mathbf{R}=\mathbf{R}(x,\alpha)\mathbf{R}(y,\beta)\mathbf{R}(z,\gamma) \tag{15}$$

$(\alpha\ ,\beta\ ,\gamma)$ is the rotation angle in the local coordinate system relative to the fixed coordinate system.

$$ {}^{O}_{Q}\mathbf{R}=\begin{bmatrix} c\alpha c\beta c\gamma\text{-}s\alpha s\gamma & \text{-}c\alpha c\beta s\gamma\text{-}s\alpha c\gamma & c\alpha s\beta \\ s\alpha c\beta c\gamma+c\alpha s\gamma & \text{-}s\alpha c\beta s\gamma+c\alpha c\gamma & s\alpha s\beta \\ \text{-}s\beta c\gamma & s\beta s\gamma & c\beta \end{bmatrix}_{3\times3} \tag{16}$$

$$\mathbf{DT=W} \tag{17}$$

$$\mathbf{D}=\begin{bmatrix} \mathbf{U}_1 & \mathbf{U}_2 & \cdots & \mathbf{U}_7 \\ {}^{O}_{Q}\mathbf{R}\overrightarrow{QP_1}\times\mathbf{U}_1 & {}^{O}_{Q}\mathbf{R}\overrightarrow{QP_2}\times\mathbf{U}_2 & \cdots & {}^{O}_{Q}\mathbf{R}\overrightarrow{QP_7}\times\mathbf{U}_7 \end{bmatrix} \tag{18}$$

$T=[t_1\ \ t_2 \ldots t_7]^T$ is the vector composed of the pull forces of the seven driving ropes.

$$\mathbf{W}=\begin{bmatrix} \mathbf{F_R} \\ \mathbf{M_R} \end{bmatrix} \tag{19}$$

Kinetic model of rehabilitation belt: the kinetic model of the rehabilitation belt is given below in figure 6.

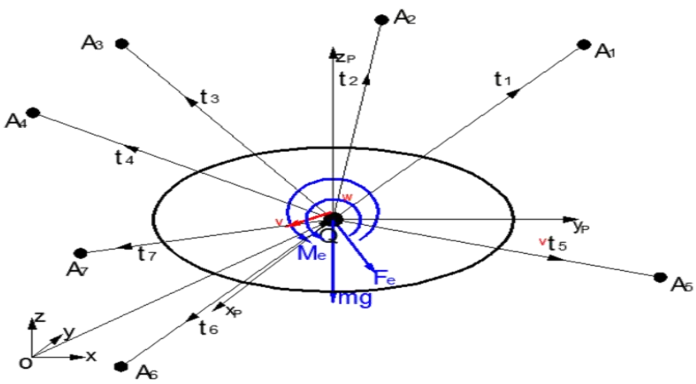

Figure 6. Kinetic model of the rehabilitation belt

$\mathbf{r} \in \mathbf{R^3}$ is the position vector of the center of mass of the rehabilitation belt relative to the reference point Q.$\mathbf{F}_e \in \mathbf{R^3}$ and $\mathbf{M}_e \in \mathbf{R^3}$ is respectively the external force and the external torque applied to the reference point Q of rehabilitation belt without including the effect of gravity. The dynamic equation of the rehabilitation device with respect to the rehabilitation belt reference point Q:

$$\begin{cases} \sum_{i=1}^{7} \mathbf{t}_i+\mathbf{f}_q+m\mathbf{g}\text{-}m\dot{\mathbf{v}}=0 \\ \sum_{i=1}^{7} {}^{O}_{Q}\mathbf{R}\overrightarrow{QP_i}\times\mathbf{t}_i+\mathbf{M}_q\text{-}\mathbf{I_q}\dot{\mathbf{w}}\text{-}\mathbf{w}\times(\mathbf{I_q}\mathbf{w})=0 \end{cases} \tag{20}$$

m is the mass of the pelvis, $\mathbf{f}_q$ is the external force applied to the pelvis, $\mathbf{M}_q$is the external torque applied to the pelvis, $\mathbf{I_q}$ is the inertia tensor of the pelvis at Q, $\mathbf{v}$ is the velocity of the pelvis at Q, ω is the angular velocity of the point Q, $\mathbf{g}=[0\quad 0\quad g]^T$is the gravitational acceleration vector.

$$\mathbf{DT=B} \tag{21}$$

$$\mathbf{B}=\begin{bmatrix} \mathbf{f}_q+m\mathbf{g}\text{-}m\dot{\mathbf{v}} \\ \mathbf{M}_q\text{-}\mathbf{I_q}\dot{\mathbf{w}}\text{-}\mathbf{w}\times(\mathbf{I_q}\mathbf{w}) \end{bmatrix} \tag{22}$$

Kinetic model of drive mechanism: the kinetic model of guide wheel is given in figure 7. $\boldsymbol{\theta}$ is the rotation angle of the guide wheel, J_i is the equivalent moment of inertia of the guide wheel, $\boldsymbol{\tau_i}$ is the torque generated by the motor, **t** is the tension of the rope, **C** is the equivalent damping coefficient of the guide wheel and **r** is the equivalent radius of the guide wheel.

$$\mathbf{J\ddot{\theta}+C\dot{\theta}+rt=\tau} \tag{23}$$

$$\mathbf{t=1/r\left(\tau-J\ddot{\theta}-C\dot{\theta}\right)} \tag{24}$$

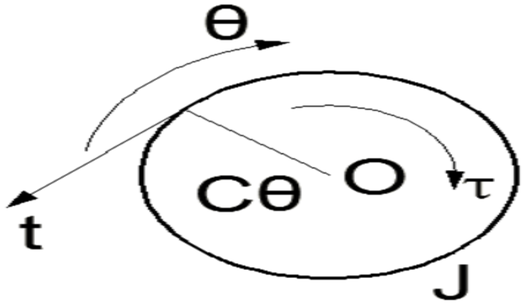

Figure 7. Kinetic model of guide wheel

Dynamic model of the system: the kinetic model of the belt and the kinetic model of the drive mechanism are used to solve the dynamic model of the system. Suppose **θ=0**, the guide wheel rotates clockwise, **θ** is negative, the change amount of the rope length of the guide wheel.

$$r\boldsymbol{\theta}_{\mathbf{i}}=-\Delta\mathbf{L}_{\mathbf{i}} \tag{25}$$

$$\Delta\mathbf{L}_{\mathbf{i}}=\mathbf{L}_{\mathbf{i}}'-\mathbf{L}_{\mathbf{i}} \tag{26}$$

$\mathbf{L}_{\mathbf{i}}'$ is the current length of the $\boldsymbol{i}$ rope, $\mathbf{L}_{\mathbf{i}}$ is the initial length of the $\boldsymbol{i}$ rope.

$$\boldsymbol{\theta}_{\mathbf{i}}=\frac{1}{r\left(\mathbf{L}_{\mathbf{i}}'-\mathbf{L}_{\mathbf{i}}\right)} \tag{27}$$

$$\mathbf{X}=[x \quad y \quad z \quad 0 \quad 0 \quad \gamma]^{\mathbf{T}} \tag{28}$$

$$\dot{\mathbf{X}}=[\mathbf{v} \quad \mathbf{w}]^{\mathbf{T}} \tag{29}$$

$$\ddot{\mathbf{X}}=[\dot{\mathbf{v}} \quad \dot{\mathbf{w}}]^{\mathbf{T}} \tag{30}$$

$$\dot{\boldsymbol{\theta}}={}^{\partial\boldsymbol{\theta}}/_{\partial\mathbf{X}}\,\dot{\mathbf{X}} \tag{31}$$

$$\ddot{\boldsymbol{\theta}}=d/dt\left({}^{\partial\boldsymbol{\theta}}/_{\partial\mathbf{X}}\right)\dot{\mathbf{X}}+{}^{\partial\boldsymbol{\theta}}/_{\partial\mathbf{X}}\,\ddot{\mathbf{X}} \tag{32}$$

$$\mathbf{t}=\frac{\mathbf{1}}{\mathbf{r}\left(\boldsymbol{\tau}\mathbf{-J}\left(d/dt\left({}^{\partial\boldsymbol{\theta}}/_{\partial\mathbf{X}}\right)\dot{\mathbf{X}}+{}^{\partial\boldsymbol{\theta}}/_{\partial\mathbf{X}}\ddot{\mathbf{X}}\right)\mathbf{-C}\left({}^{\partial\boldsymbol{\theta}}/_{\partial\mathbf{X}}\dot{\mathbf{X}}\right)\right)} \tag{33}$$

$$\frac{\mathbf{D}}{\mathbf{r}\left(\boldsymbol{\tau}\mathbf{-J}\left(d/dt\left({}^{\partial\boldsymbol{\theta}}/_{\partial\mathbf{X}}\right)\dot{\mathbf{X}}+{}^{\partial\boldsymbol{\theta}}/_{\partial\mathbf{X}}\ddot{\mathbf{X}}\right)\mathbf{-C}\left({}^{\partial\boldsymbol{\theta}}/_{\partial\mathbf{X}}\dot{\mathbf{X}}\right)\right)}=\mathbf{B} \tag{34}$$

Design of Controlled Driving System

In the standing rehabilitation stage, the human pelvis rotate along the xyz to achieve three degrees of rotation movement, which is 3R movement. In the walking rehabilitation stage, the human pelvis mainly move along the xyz three directions and rotate along the **z** axis. Seven ropes are attached to the seven points of the rehabilitation belt. The force sensor on each rope measures the tension on the rope. The displacement sensor on the belt measures the position of the lumbar rehabilitation. In the rehabilitation process, the device outputs required force and position.

Fuzzy sliding mode control of single rope: the device drives the lumbar parallel rehabilitation through seven ropes to reinforce the rehabilitation force and rehabilitation position required for the rehabilitation belt. The control of a single rope unit affects the control performance of the whole control system. The force signal is sensitive and easy to fluctuate. In this paper, a fuzzy sliding mode controller is used to control a single rope unit. Principle of fuzzy sliding mode control for single rope is illustrated in figure 8.

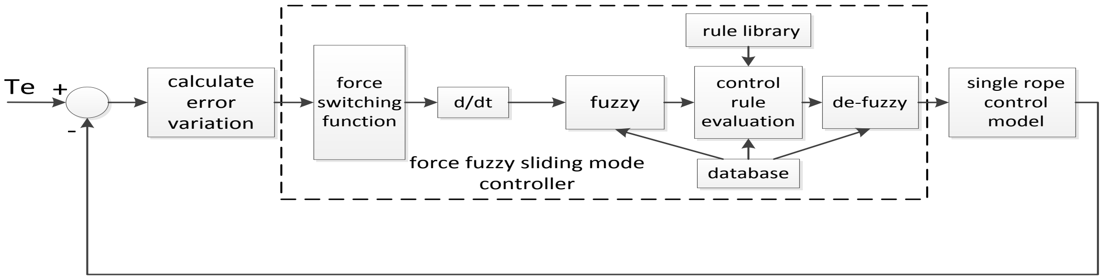

Figure 8. Principle of fuzzy sliding mode control

From the basic theory of sliding mode, S and $\dot{S}$ at any point on the plane of the phase represents the relative distance between the point and the sliding surface and the relative velocity of the sliding surface. According to experience, use fuzzy sliding mode control rules to adjust the size of the control variable u, to ensure the accessibility
condition $S\dot{S}<0$.

Set the tension command signal Te, the rope tension error e_f, c_f is a constant and tension rate error rate change ec_f as the state variable. The input language variables of the force fuzzy controller are the tension switching function e_{fs} and its change rate ec_{fs}, and the output language variable is the controller's change amount Δu_{fs}.Tension switching function can be attained:

$$e_{fs}=S_f=c_f.c_f+ec_f \quad (35)$$

The fuzzy set and the domain are defined as follows: the fuzzy sets of all variables are: {NB NM NS ZO PS PM PB}.N is "negative ", P is "positive", B is " big", M is "middle", S is "small", ZO is “zero” ,

The subordinate function curve has a higher resolution and a higher control sensitivity. The shape of the membership function curve is gentler, the control characteristic is also gentler, and the stability of the system is better. The objective of using fuzzy sliding mode control is to soft the control signal and reduce or avoid the buffeting phenomenon. So a normal distribution membership function is chosen.

Simulation Result Analysis

Lumbar rehabilitation in patients divided into two stages. The first stage is standing rehabilitation stage, this stage does not need the movement of the patient's lumbar xyz three directions, and only needs to achieve the movement of flexion, extension, scoliosis and rotation, which means the rotation angle (α, β, γ) changes in the process. The second stage is walking rehabilitation stage and patients try to be consistent with the normal walking gait.

Standing rehabilitation stage: according to the mechanical structure, the following data are obtained:

$$\overrightarrow{OA_1}=[1500 \quad 750 \quad 2000]^T \qquad \overrightarrow{OA_2}=[750 \quad 1500 \quad 2000]^T \qquad \overrightarrow{OA_3}=[0 \quad 750 \quad 2000]^T$$
$$\overrightarrow{OA_4}=[750 \quad 0 \quad 2000]^T$$
$$\overrightarrow{OA_5}=[1500 \quad 1500 \quad 0]^T \quad \overrightarrow{OA_6}=[0 \quad 0 \quad 0]^T$$
$$\overrightarrow{OA_7}=[0 \quad 1500 \quad 0]^T \qquad \overrightarrow{OQ}=[750 \quad 750 \quad z]^T \quad (36)$$

The value of z is changed according to the height of the patients’ lumbar. Coordinate of the rehabilitation belt is given below in Figure 9 and the radius of the belt is R.

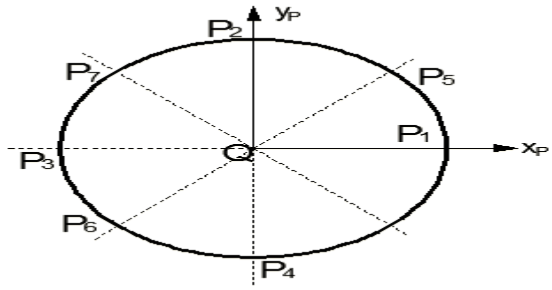

Figure 9. Coordinate of the rehabilitation belt.

$$\overrightarrow{QP_1}=[R \quad 0 \quad 0]^T \qquad \overrightarrow{QP_2}=[0 \quad R \quad 0]^T \qquad \overrightarrow{QP_3}=[-R \quad 0 \quad 0]^T$$

$$\overrightarrow{QP_4}=[0 \quad -R \quad 0]^T \qquad \overrightarrow{QP_5}=\left[\frac{\sqrt{2}}{2}R \quad \frac{\sqrt{2}}{2}R \quad 0\right]^T \qquad \overrightarrow{QP_6}=\left[-\frac{\sqrt{2}}{2}R \quad -\frac{\sqrt{2}}{2}R \quad 0\right]^T$$

$$\overrightarrow{QP_7}=\left[-\frac{\sqrt{2}}{2}R \quad \frac{\sqrt{2}}{2}R \quad 0\right]^T \tag{37}$$

$$\overrightarrow{A_1'A_1}=[0 \quad y_1 \quad 0]^T \qquad \overrightarrow{A_2'A_2}=[x_2 \quad 0 \quad 0]^T \tag{38}$$

$$\overrightarrow{A_3'A_3}=[0 \quad y_3 \quad 0]^T \qquad \overrightarrow{A_4'A_4}=[x_4 \quad 0 \quad 0]^T \tag{39}$$

The theoretical length L_i $(i=1,2\ldots7)$ of seven ropes is known to solve the position vector of the moving platform $Q(\alpha, \beta, \gamma)$ in the fixed coordinate system. z=1040 , R=77,$y_1=x_2=y_3=x_4=20$.

According to the data of medical experiment, the lowest value of rotation was selected as the initial value of training exercise. Flexion is 33°, extension is 17°, scoliosis is 22°, rotation is 17°. The trajectory equation for constructing the rotational angle is as follows:

$$\begin{cases} L_1'=\sqrt{[750-R(c\alpha c\beta c\gamma-s\alpha s\gamma)]^2+\left[R(s\alpha c\beta c\gamma+c\alpha s\gamma)-y_1\right]^2+(2000-z+Rs\beta c\gamma)^2} \\ L_2'=\sqrt{[R(c\alpha c\beta s\gamma+s\alpha c\gamma)-x_2]^2+[750+R(s\alpha c\beta s\gamma-c\alpha c\gamma)]^2+(2000-z-Rs\beta s\gamma)^2} \\ L_3'=\sqrt{[-750+R(c\alpha c\beta c\gamma-s\alpha s\gamma)]^2+\left[R(s\alpha c\beta c\gamma+c\alpha s\gamma)-y_3\right]^2+(2000-z-Rs\beta c\gamma)^2} \\ L_4'=\sqrt{[R(c\alpha c\beta s\gamma+s\alpha c\gamma)-x_4]^2+[-750+R(-s\alpha c\beta s\gamma+c\alpha c\gamma)]^2+(2000-z+Rs\beta s\gamma)^2} \\ L_5'=\sqrt{\left[750-\frac{\sqrt{2}}{2}R(c\alpha c\beta c\gamma-s\alpha s\gamma-c\alpha c\beta s\gamma-s\alpha c\gamma)\right]^2+750-\frac{\sqrt{2}}{2}R(s\alpha c\beta c\gamma+c\alpha s\gamma-s\alpha c\beta s\gamma+c\alpha c\gamma)+\left[-z-\frac{\sqrt{2}}{2}R(-s\beta c\gamma+s\beta s\gamma)\right]^2} \\ L_6'=\sqrt{\left[-750+\frac{\sqrt{2}}{2}R(c\alpha c\beta c\gamma-s\alpha s\gamma-c\alpha c\beta s\gamma-s\alpha c\gamma)\right]^2+\left[-750+\frac{\sqrt{2}}{2}R(s\alpha c\beta c\gamma+c\alpha s\gamma-s\alpha c\beta s\gamma+c\alpha c\gamma)\right]^2+\left[-z+\frac{\sqrt{2}}{2}R(-s\beta c\gamma+s\beta s\gamma)\right]^2} \\ L_7'=\sqrt{\left[-750+\frac{\sqrt{2}}{2}R(c\alpha c\beta c\gamma-s\alpha s\gamma+c\alpha c\beta s\gamma+s\alpha c\gamma)\right]^2+\left[750+\frac{\sqrt{2}}{2}R(s\alpha c\beta c\gamma+c\alpha s\gamma+s\alpha c\beta s\gamma-c\alpha c\gamma)\right]^2+\left[-z+\frac{\sqrt{2}}{2}R(-s\beta c\gamma-s\beta s\gamma)\right]^2} \end{cases} \tag{40}$$

$$\begin{cases} \alpha=21\sin\left(\frac{t\pi}{10}+\frac{\pi}{2}\right) \\ \beta=17\sin\left(\frac{t\pi}{10}+\pi\right) \\ \gamma=17\sin\left(\frac{t\pi}{10}+\pi\right) \end{cases} \tag{41}$$

The rotational angle equation of the rehabilitation belt of equation is substituted into the calculation equation of rope length and the change rule of length of rope is solved by using MATLAB, which is given in Figure 10.The speed of seven ropes is given below in Figure 11.

Walking rehabilitation stage: the motion trajectory of the pelvis in the upper and lower, front and back, left and right directions is similar to the normal curve. Take the healthy male as an example, the motion trajectory equation of the pelvis is as follows.

$$\begin{cases} x=750+25\sin(5t+\pi/2) \\ y=750+10\sin(10t+\pi) \\ z=1040+10\sin(10t+\pi/2) \\ \gamma=4\sin(5t) \end{cases} \tag{42}$$

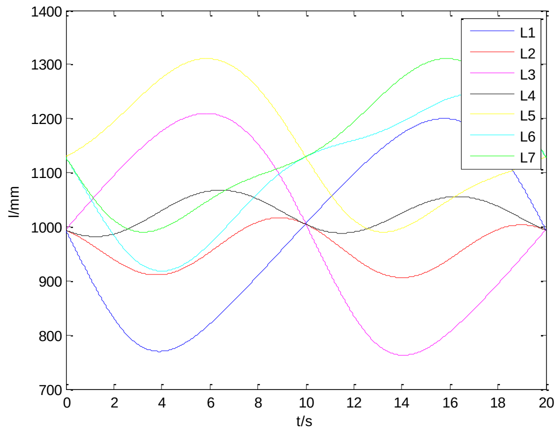

Figure 10. Length of seven ropes

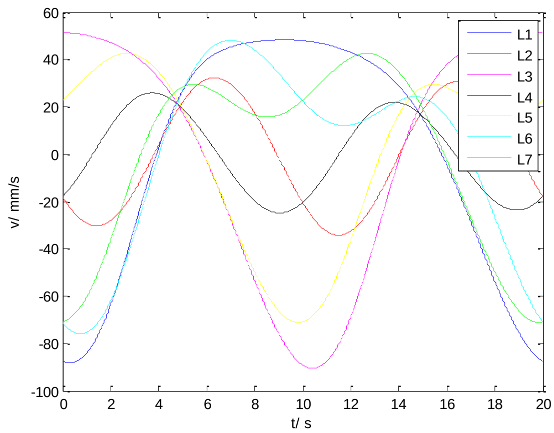

Figure 11. Speed of seven ropes

Use MATLAB to figure out walking trajectory and walking process position, which is given in Figure 12 and Figure 13.

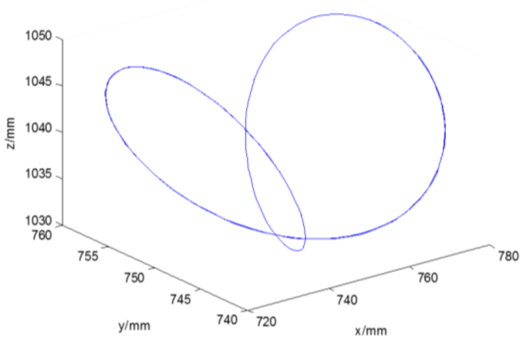

Figure 12. Walking trajectory of patient

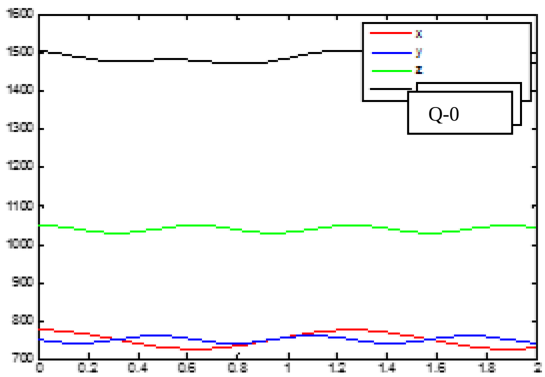

Figure 13. Position of walking process

Conclusions

According to the mechanical structure, the kinematic and dynamic equations are used to analyze the kinematic curves of the ropes during the rehabilitation process. The rehabilitation training is realized in two modes: standing rehabilitation and walking rehabilitation. Based on the design of fuzzy sliding mode controller, it can realize the output of the rehabilitation process of patients with the needed force and movement, so the patients achieve better rehabilitation.

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