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# Research on Active Training Model of Rehabilitation Robot Based on Joint Torque Signal

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**Abstract.** This paper constructs a man-machine integrated no-load static model considering the self-balancing of the mechanism, obtains the mapping relationship among joint variable, no-load torque, measured torque and end-force of the patient. According to the damping control strategy, the end force and speed mapping function planning is completed. The joint angular velocities based on the kinematic inverse solution are calculated, which are important parameter of man-machine coupling motion.

## 1 Introduction

The number of patients with stroke and physical disabilities is increasing day by day. Replacing rehabilitation doctors with rehabilitation robots in repeated rehabilitation training is a requirement of modern social development[1]. Lokomat is a suspended lower limb rehabilitation robot that truss the patient's body up through a rope [2,3]. The same products include the German WOODWAY lower limbs step training system[4], Lopes developed by Twente University[5], and Flexbot developed by Jinghe Company in China[6]. It has problems such as poor wear and only be used to the patients whose lower limbs have basic supporting strength. For patients with early and middle limb injuries, the horizontal lower limb rehabilitation robot can avoid the problem of unable to support their body weight due to limb weakness. The MotionMaker in Switzerland uses a mechanical leg mechanism similar to the lower limbs of the human body[7]. That enables the patient to recover in sitting and lying posture. Yaskawa Corporation of Japan developed LR2, mainly for passive training. Yanshan University developed a lower limb rehabilitation robot[8], which is the closest horizontal clinical

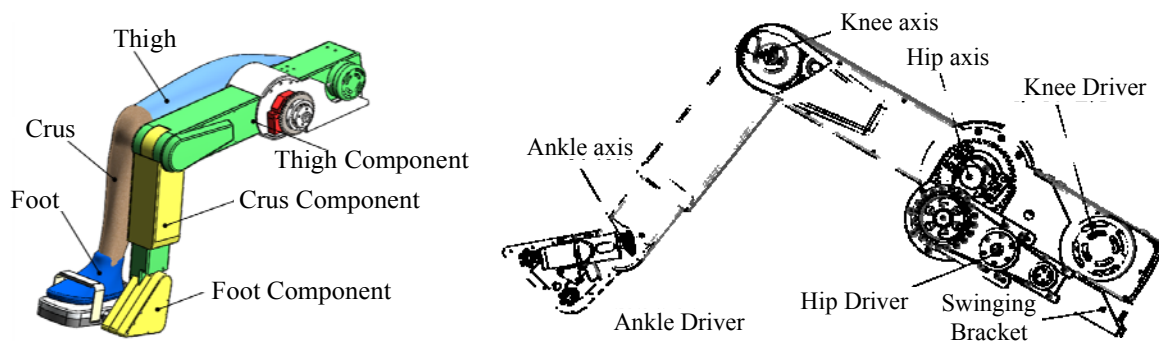


rehabilitation robot in China.

Most of the above-mentioned lower limb rehabilitation robots use the electromyography signal or the pressure sensor in the active assist/impedance training mode. It cannot accurately quantify the torque of patient's joint by the myoelectric signal that can judge the direction muscles want to move. The lower limb rehabilitation robot designed in this paper places the torque sensor in the joint. Through the static modeling and calibration of the robot the active training control strategy of the patient is studied.

## 2 Mechanical design

In order to adapt patients to sagittal rehabilitation training, the mechanical leg drives the three joints, as fig.1 shows. The hip rotation axis has located the center of thigh component. The knee joint driver and the swinging bracket which can effectively balance the weight of the thigh and foot components are installed at the end. The hip and knee joints are both superimposed by the belt drive and the gear transmission to realize the long torque output of the joint. The large motor output torque error has a terrible influence on the dynamic control of the manipulator. Therefore the installation of torque sensors and absolute position encoders can improve the accuracy of the robot.



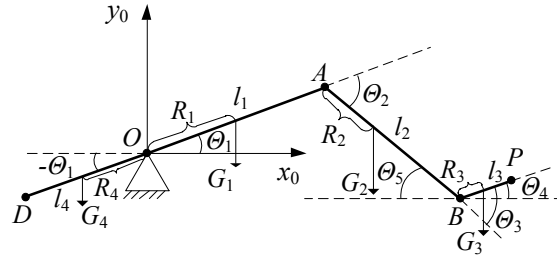
**Figure 1.** The mechanical design of the robot

## 3 Static analysis of lower limb rehabilitation robot

The robot was running at low speed and steady state, ignoring the dynamics [9]. And torque signal collected at the joint from the leg's weight of the mechanical and human body. To separate the force applied by patients, the static analysis of the lower limb rehabilitation robot model was performed, and the mapping relationship between the joint no-load moment and the angle was obtained.

### 3.1 Considering self-balancing static load static model

Simplified the mechanical leg model of the lower limb rehabilitation robot into a planar three-link series mechanism. The specific model show in Fig.2.



**Figure 2.** Leg model of a lower limb rehabilitation robot

Upper formula can be corrected to consider the mechanism installation error, friction and the fit of the human-machine fit.

$$\begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix} = \begin{bmatrix} \cos \theta_1 & \cos(\theta_1 + \theta_2 + \theta_3) & \cos(-\theta_2 - \theta_1) \\ 0 & \cos(\theta_1 + \theta_2 + \theta_3) & \cos(-\theta_2 - \theta_1) \\ 0 & 0 & \cos(-\theta_2 - \theta_1) \end{bmatrix} \begin{bmatrix} G_3 l_1 + G_2 l_1 + G_1 R_1 - G_4 R_4 + f_1 \\ G_3 l_2 + G_2 R_2 + f_2 \\ G_3 R_3 + f_3 \end{bmatrix} \quad (1)$$

Abbreviate as:

$$\mathbf{M}_{3 \times 1} = \mathbf{L}_{3 \times 3}(\theta) \cdot \mathbf{C}_{3 \times 1} \quad (2)$$

### 3. 2 Static calibration using engineering methods

The feature parameters in Eq. 2 are associated with patient information and are unique to any patient. In the training process, the real-time angle of the hip and knee joint can be monitored by the absolute position encoder at the joint. Torque sensors can real-time measure the torque at the joint that was produced by the patient exerting force at the end of the mechanical leg.

$$\mathbf{M}_s = \mathbf{M}_h + \mathbf{M} \quad (3)$$

When the patient does not exert force, the measured torque is the no-load torque. The analysis of the variable term of Eq. 1 shows that  $\mathbf{L}_{3 \times 3}(\theta)^{-1}$  exists in the range of motion and  $\theta_1 \neq 90^\circ, \theta_1 + \theta_2 + \theta_3 \neq 90^\circ, -\theta_2 - \theta_1 \neq 90^\circ$  which can be expressed by Eq.4.

$$\mathbf{C}_{3 \times 1} = \mathbf{L}_{3 \times 3}(\theta)^{-1} \cdot \mathbf{M}_{3 \times 1} \quad (4)$$

The length between the two joints was adjusted, and the weight of the limb cannot change. Therefore, the characteristic parameters  $\mathbf{C}_{3 \times 1}$  in Eq.2 are unchanged. The ankle joint moved in a lower speed  $v$  at the time that patients do not exert force. Record the foot pressure value  $f_{zd}$  at intervals of  $\Delta t$  and calculate the joint angles  $\theta_1, \theta_2, \theta_3$ . The joint angle is recorded  $k$  times. Then the knee and hip joints were rotated in the same way to record  $k$  knee torque values  $M_2, M_1$  and angle values  $\theta_1, \theta_2, \theta_3$ . Then the  $f_{zd}, \theta_3, \theta_2, \theta_1$  were converted into  $M_1, \theta_4, \theta_5$ . According to formula (2),  $C_{31}, C_{21}$  and  $C_{11}$  are calculated.

$$M_{3i} = \cos \theta_{5i} C_{31i} \quad (i=1-k)$$

$$\bar{C}_{31} = \frac{1}{k} \sum_{i=1}^k \frac{M_{3i}}{\cos \theta_{5i}} \quad (5)$$

$$M_{2i} = \cos \theta_{4i} C_{21i} + \cos \theta_{5i} \bar{C}_{31} \quad (i=1-k)1$$

$$\bar{C}_{21} = \frac{1}{k} \sum_{i=1}^k \frac{M_{2i} - \cos \theta_{5i} \bar{C}_{31}}{\cos \theta_{4i}} \quad (6)$$

$$M_{li} = \cos \theta_{li} C_{1li} + \cos \theta_{4i} \bar{C}_{21} + \cos \theta_{5i} \bar{C}_{31} \quad (i=1-k)$$

$$\bar{C}_{11} = \frac{1}{k} \sum_{i=1}^k \frac{M_{li} - \cos \theta_{5i} \bar{C}_{31} - \cos \theta_{4i} \bar{C}_{21}}{\cos \theta_{4i}} \quad (7)$$

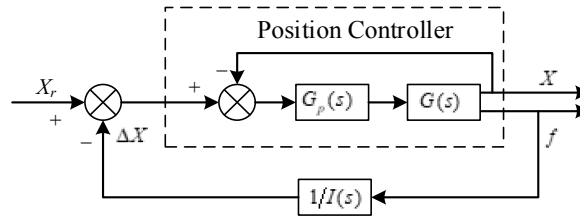
Combining Eq.5, Eq.6, Eq.7 gives:

$$C_{3 \times 1} = \begin{bmatrix} \bar{C}_{11} \\ \bar{C}_{21} \\ \bar{C}_{31} \end{bmatrix} \quad (8)$$

After solving the characteristic parameters, the mapping relationship between the joint no-load torque and joint variables is found, that is, Eq.2 can be solved.

#### 4 Damped control strategy training mode

The basic idea of the impedance control strategy is to adjust the impedance parameters of the end effector so that the position and contact force satisfy an ideal dynamic relationship [10], which is called stiffness and damping control. This paper uses a location-based damping control strategy, the basic implementation of that can be as shown in Fig.3.



**Figure. 3** The basic mode of the damping control strategy

The terminal dynamics expression of the robot can be represented by the following Ep.9[11].

$$M_d(\ddot{X}_r - \ddot{X}) + B_d(\dot{X}_r - \dot{X}) + K_d(X_r - X) = f \quad (9)$$

The transfer function corresponding to equation (3-52) is:

$$I(s) = \frac{F(s)}{\Delta X(s)} = M_d s^2 + B_d s + K_d \quad (10)$$

Considering the adaptability and safety of patients in clinical application, the lower limb rehabilitation robot was speed-limited. Therefore, the second-order differential term  $M_d(\ddot{X}_r - \ddot{X})$  in Eq.10 can be neglected without considering the transient collision process of human-machine coupling motion. When the damping control method is adopted, the stiffness term is not considered, and the  $K_d(X_r - X)$  term can be ignored. Therefore, the Ep.10 can be simplified to the damping control type.

$$f = B_d \Delta \dot{X} \quad (11)$$

#### 5 End force and end speed mapping function planning

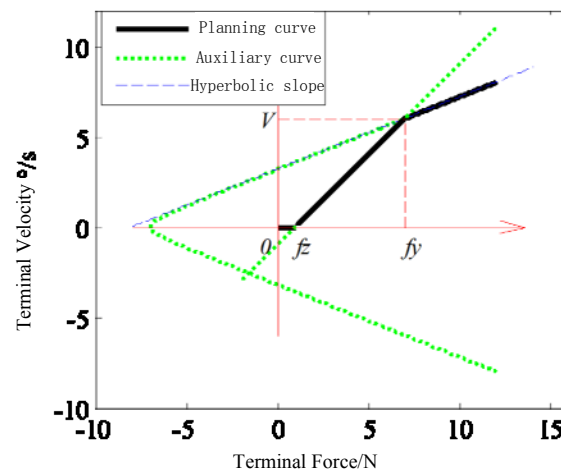
The velocity of the robot end follows the tangent direction of the preset trajectory in each control loop, so the vector direction of the force does not have any control significance.

$$f = B(v_0) \quad (12)$$

At the same time, the end speed can also be expressed as a function of the end force, ie:

$$v_0 = g(f) \quad (13)$$

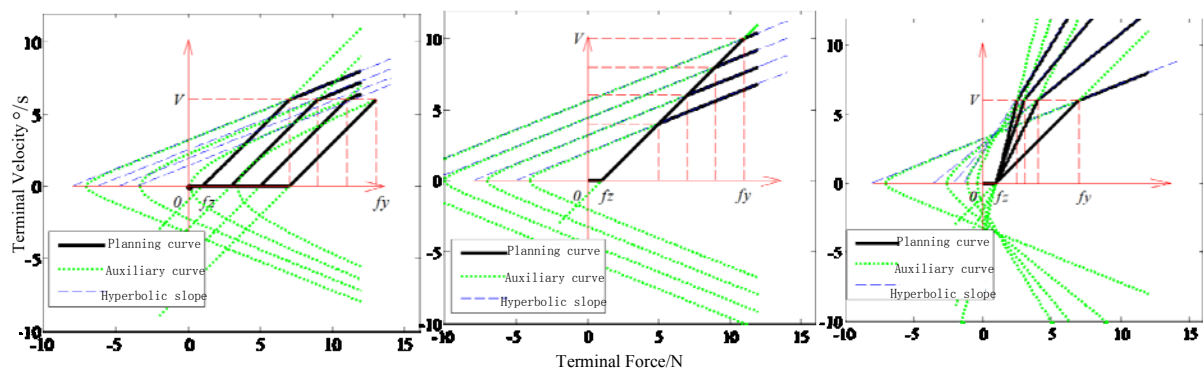
The planned mapping curve can be as shown in Fig.4.



**Figure. 4** End speed planning

Fig.5 is the trend of influence of parameters on terminal velocity under starting threshold, maximum linear velocity and slope of control variables. By reasonably configuring the three parameters, the patients can be trained at different levels. In the actual use of human-computer interaction, the dialog box of parameter setting options will provide default parameters and give the range of extreme motion.

The terminal velocity is the connection direction of two adjacent interval points in the preset trajectory. Each interval points and the left and right adjacent interval points form two opposite directions.



**Figure. 5** Effect of Starting threshold、Max Velocity、Slope on terminal velocity

## 6. Conclusion

In summary, this paper proposes a lower limbs rehabilitation robot and an active training model base on joint torque. Obtains the mapping relationship among joint variable, no-load torque, measured torque and end-force of the patient. Explore the effect of different control parameters on terminal velocity. It provides a basis for further study of patient training trajectory comfort.

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