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Trajectory planning and mechanic's analysis of lower limb rehabilitation robot

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Abstract. A new rehabilitation robot was designed. The robot included a suspension mechanism, a drive unit, and an adjustment mechanism. Additionally, innovative weight loss mechanism increased the dynamical device so that it could be used with patients of varying lower extremity muscle strengths. The relationship of hip and knee angles with height, step length, and gait cycle was studied. It was developed to generate different trajectories for different patients. Kinematics and dynamics were studied to lay the foundation for control.

Keywords: Rehabilitation robot, medical design, trajectory planning, dynamics, kinematics

1. Introduction

Due to rapid aging, increased incidence of stroke, paralysis resulting from vehicle accidents, and other physical impairments, traditional manual rehabilitation and simple medical rehabilitation equipment often do not meet the immediate requirements of disabled people [1]. Therefore, a lower limb rehabilitation robot that can assist patients in rehabilitation training was investigated.

In 2006, Germany developed the Lokohelp [2] rehabilitation robot. A weight loss mechanism, an electric treadmill, walker, and medical treadmill are included in the robot. However, the robot offers no support for a patient's thigh, making it unsuitable for patients who do not have the capacity to carry their own weight. The American company Healthsouth developed the Auto Ambulator robot [3]. It consists of two-DOF manipulators driven by two motors. It tracks the thigh and calf of the patient to operate. However, the robot does not take the displacement of the center of gravity in a moving person into account, resulting in an unnatural gait.

This article describes a new suspension device with which weight loss can be achieved dynamically. Its trajectory can be generated based on different heights, step sizes, and walking cycles. Kinematics and dynamics of the robot were studied in order to achieve the goal of patient rehabilitation.

2. Mechanical design of the lower limb rehabilitation robot

A rehabilitation robot not only must accommodate different heights and weights, but must also monitor the patient's rehabilitation status [4]. Based on the above requirements of a rehabilitation robot, a lower limb hydraulic-driven rehabilitation robot was designed. It consisted of the following fea-

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tures: 1.) The suspension device was designed to decrease the force on a patient's lower limb when his muscle strength does not support his own body weight; 2.) The suspension device maintains the patient's balance when he is unable to maintain balance during training; 3.) The pelvis width of the robot, the length of the robot's leg, and the height of the pelvis from the ground can be adjusted in order to suit different patients.

Reference [5] refers to angle changes of each joint when one is walking normally. The range of the hip joint motion is -15° to 30° and the range of the knee joint motion is -15° to 30° in the sagittal plane. Both have almost no movement in the coronal and horizontal planes. The range of the ankle joint motion is very small in the sagittal plane. The biggest energy consumption occurs in the hip and knee while walking [6]. Walking in the sagittal plane of the robot completes a patient's gait learning process. The DOF of the robot was determined as four. A valve-controlled asymmetric cylinder was selected to drive the robot's movements.

The length of the average person's thigh is 390 mm to 420 mm. To accommodate different patients' legs, the robot was designed to be adjusted using the leg clamp. The range of adjustment of the robot was the same as the length of the average thigh. In order to ensure people of different heights could use the robot for rehabilitation, the height of the hip joint of the robot from the ground was 710 mm-940 mm.

In the normal course of human movement, the center of gravity movement shows similar trends of sinusoidal motion. The position of the pelvis of the rehabilitation robot in the course of the campaign showed sinusoidal trajectory with the body's normal walking gait. A weight reduction device, shown in Figure 1, was designed. It was composed of a sling, pulley block, and spring. With the help of the spring, the robot could move in the vertical direction.

3. Trajectory planning of the lower limb rehabilitation robot

The CGA (clinical gait analysis) [7] data of human movement was obtained from hospitals. In a patient's rehabilitation process, moving trajectories should be placed based on an individual patient's characteristics. This is an urgent problem of rehabilitation robots for most scholars [8]. This article used curve fitting based on the body's CGA data to obtain a knee and hip angle curve fitting formula during normal body movement, from which trajectory rehabilitation could be generated based on the positive and inverse kinematics.

The human gait cycle was set as T seconds and the key point θ was taken every 0.02 T, for the point of the curve fitting. Polynomial fitting, Fourier fitting, Gaussian fitting, and Sum of Sin fitting were used to fit the point. The results are shown in Figure 2.

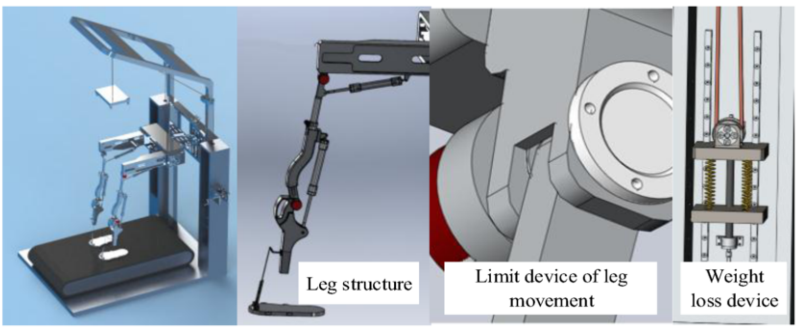

Fig. 1. The overall assembly drawing of the rehabilitation robot.

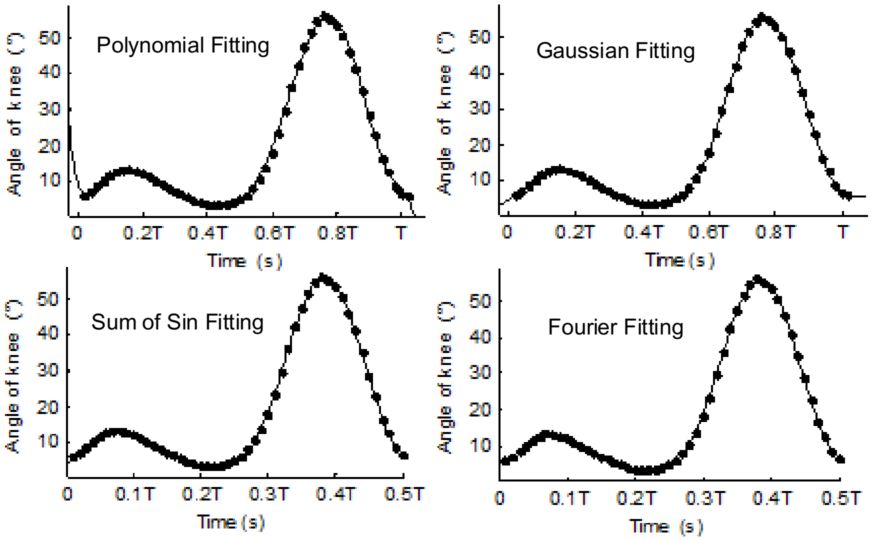

Fig. 2. Knee angle curve with four curve fitting methods.

Table 1 shows the frequency of the resulting equations, and variance and RMS with these four methods. The data in the table shows that the number of Fourier fitting equations was the minimum, and the variance of the Gaussian fitting SSE and RMSE was the minimum with a frequency of 8. In the actual control of the system, it had great influence on real-time control. The Sum of Sin fitting had a high frequency, and the variance and RMSE value were normal. Moreover, the number of Fourier fitting was low, but the SSE and RMS were smaller. The Fourier fitting method was selected to get the hip joint fit to the data.

Similarly, the four methods above were used for the hip angle curve fitting.

The use of Fourier relations hip movement angle fitting method and the resulting angle of knee movement and time were as follow. The values of parameters in Eq. 1 were shown in Table 2.

$$\theta(\mathrm{t}) = \mathrm{a}_0 + \sum_{i=1}^{3} a_i \cos(\omega * \mathrm{i} * \mathrm{t} *) + \sum_{i=1}^{3} b_i \sin(\omega * \mathrm{i} * \mathrm{t} *) \quad (1)$$

Table 1

Knee angle fitting method statistics table

Curve Fitting method	Frequency	SSE	RMSE
Polynomial Fitting	9	8.4557	0.7520
Gaussian Fitting	8	2.324	0.15736
Sum of Sin Fitting	4	5.1328	0.3628
Fourier Fitting	3	6.7547	0.3965

Table 2

The value of parameters in Eq. 1

	a_0	a_1	a_2	a_3	b_1	b_2	b_3	ω
Hip	11.44	20.86	-2.364	-0.6269	-1.978	-2.684	1.205	2π/T
Knee	19.15	2.039	-13.53	-1.434	-19.1	1.742	4.176	

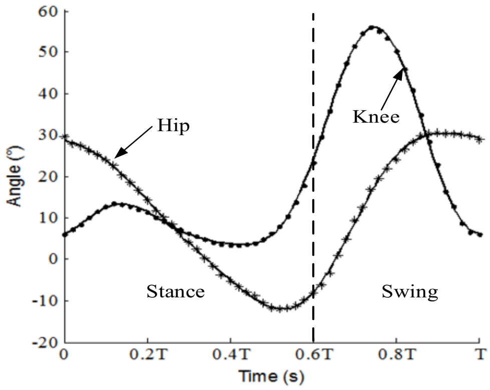

Fig. 3. Hip and Knee angle curve with Fourier fitting.

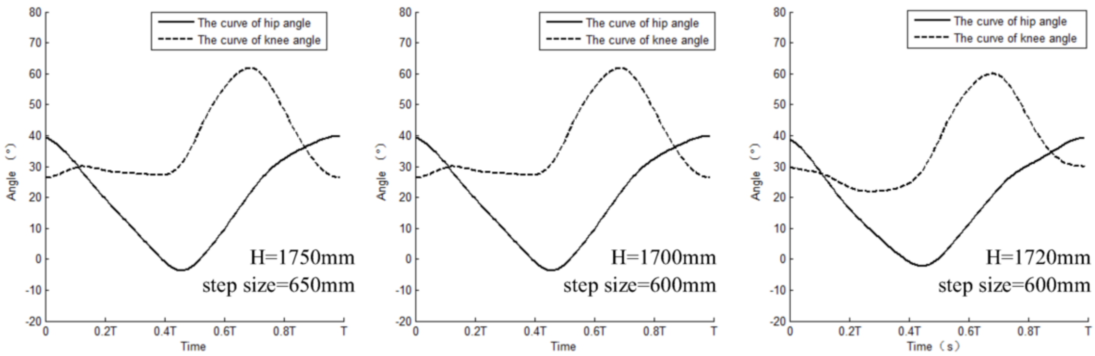

Fig. 4. Angle trajectories of different heights and different step lengths.

The results of the hip and knee curve are shown in Figure 3.

The rehabilitation robot leg can be seen as a two-bar mechanism. Based on the inverse kinematics of the two-bar mechanism, as long as the hip and ankle of the robot are known, the position and orientation of the leg can be determined. The rehabilitation robot walking motion analysis showed that the heel touches the ground for just a moment in time, and can be adjusted in the trajectory planning. So without considering the period of the heel on the ground in the process, it can be seen as an overlay process where the swing leg is walking with the support of the rear support leg.

The period of the swing phase was set as 0.5 T and the period of the stance phase was set as 0.5 T. Assuming that the left leg was regarded as the stance leg and the right leg was regarded as the swing leg, the starting point was regarded as when the distance between the right leg was behind the left leg and the left leg was the longest. The left ankle fixed location was set as the reference coordinate system origin.

Results of the coordinate ankle can be calculated according to the inverse kinematics as follows. The coordinates of the point of the left leg hip basis A were set as (x_{lhip}, y_{lhip}) at this time.

For the first half of that period can be found with:

$$\begin{cases} x_{lhip}(t) = -l_1 \sin\theta_1(t) - l_2 \sin(\theta_1(t) - \theta_2(t)) \\ y_{lhip}(t) = l_1 \cos\theta_1(t) + l_2 \cos(\theta_1(t) - \theta_2(t)) \end{cases} \tag{2}$$

The last half of that period can be found with:

$$\begin{cases} x_{lhip}(t) = -l_1 \sin\theta_1(t-0.5T) - l_2 \sin(\theta_1(t-0.5T) - \theta_2(t-0.5T)) + ps \\ y_{lhip}(t) = l_1 \cos\theta_1(t-0.5T) + l_2 \cos(\theta_1(t-0.5T) - \theta_2(t-0.5T)) \end{cases} \quad (3)$$

Coordinates for the left ankle for the first half of that period are as follow:

$$\begin{cases} x_{lankle}(t) = 0 \\ y_{lankle}(t) = 0 \end{cases} \quad (4)$$

Coordinates for the left ankle for the last half of that period are as follow:

$$\begin{cases} x_{lankle}(t) = x_{lhip}(\mathrm{t}) + l_1 \sin\theta_1(t) + l_2 \sin(\theta_1(t) - \theta_2(t)) \\ y_{lankle}(t) = y_{lhip} - l_1 \cos\theta_1(t) - l_2 \cos(\theta_1(t) - \theta_2(t)) \end{cases} \quad (5)$$

The height of people is 1750mm. The step size can be calculated as 660 mm.

H_{new} was set as the new height, ps_{new} was set as the new step size, and T_{new} was set as the new walking cycle.

$$\begin{cases} x_{lhip\_new}(t_1) = \dfrac{-l_1 \sin\theta_1(t) - l_2 \sin(\theta_1(t) - \theta_2(t))}{ps} * ps_{new} \\ y_{lhip\_new}(t_1) = \dfrac{l_1 \cos\theta_1(t) + l_2 \cos(\theta_1(t) - \theta_2(t))}{H} * H_{new} \end{cases} \quad (6)$$

$$\begin{cases} x_{lhip\_new}(t) = \dfrac{-l_1 \sin\theta_1(t-0.5T) - l_2 \sin(\theta_1(t-0.5T) - \theta_2(t-0.5T)) + ps}{ps} * ps_{new} \\ y_{lhip\_new}(t) = \dfrac{l_1 \cos\theta_1(t-0.5T) + l_2 \cos(\theta_1(t-0.5T) - \theta_2(t-0.5T))}{H} * H_{new} \end{cases} \quad (7)$$

$$\begin{cases} x_{lankle\_new}(t_1) = \dfrac{x_{lhip\_new}(t_1) + l_1 \sin\theta_1(t_1) + l_2 \sin(\theta_1(t_1) - \theta_2(t_1))}{ps} * ps\_new \\ y_{lankle\_new}(t_1) = \dfrac{y_{lhip\_new} - l_1 \cos\theta_1(t_1) + l_2 \cos(\theta_1(t_1) - \theta_2(t_1))}{H} * H\_new \end{cases} \quad (8)$$

$$l_3(t_1) = \sqrt{(x_{lhip\_new}(t_1) - x_{ankle\_new}(t_1))^2 + (y_{lhip\_new}(t_1) - y_{ankle\_new}(t_1))^2} \quad (9)$$

$$\begin{cases} \theta_{1new}(t_1) = \arccos\left(\dfrac{l_1^2 + (l_3(t_1))^2 - l_2^2}{2 * l_1 * l_3(t_1)}\right) + \arctan\dfrac{x_{ankle\_new}(t_1) - x_{hip\_new}(t_1)}{y_{hip\_new}(t_1) - y_{ankle\_new}(t_1)} \\ \theta_{2new}(t_1) = 180^\circ - \arccos\left(\dfrac{l_1^2 + l_2^2 - (l_3(t_1))^2}{2 * l_1 * l_2}\right) \end{cases} \quad (10)$$

Some data were used to verify the calculated joint angles. The data are shown in Figure 4.

4. Kinematics and dynamics of the lower limb rehabilitation robot

4.1. Kinematics of the lower limb rehabilitation robot

The rehabilitation robot used a mechanical valve-controlled hydraulic cylinder to drive the legs. The human lower limb motion model can be simplified, as shown in Figure 5. The hydraulic cylinder piston displacement curve was obtained according to CGA human motion data and hydraulic cylinder mounting position size.

The Swing phase and Support phase are 0.4 T according to the analysis on human gait. So the hydraulic cylinder displacement curve of the left and right legs can be obtained.

The hip joint hydraulic cylinder model is shown in Figure 6.

When the leg is at a standing position it is set as zero. According to the law of cosines:

$$r_p = l_3 - l_0 = \sqrt{l_1^2 + l_2^2 - 2l_1l_2\cos(\theta(t) + 90)} - l_0 \tag{11}$$

r_p: Piston displacement curve

l_1: Hydraulic cylinders in the hip and thigh fixed station installation point from the axis of rotation

l_2: The length from the high cylinder installation point to the rotary shaft

l_3: The length of the hydraulic cylinder and piston rigid

l_0: The length of the cylinder body when standing

θ_1 : The angle between the vertical line and thigh during swing

The knee joint hydraulic cylinder piston displacement can be obtained in accordance with the method for finding hip joints of hydraulic cylinder displacement. The formula is as follows:

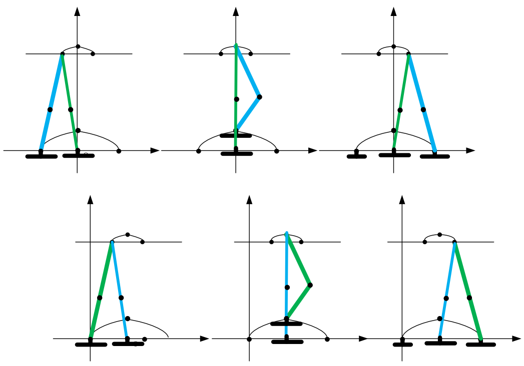

Fig. 5. Schematic of human movement.

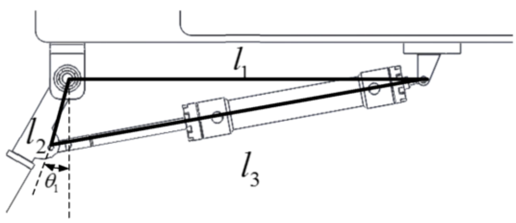

Fig. 6. Hip hydraulic cylinder.

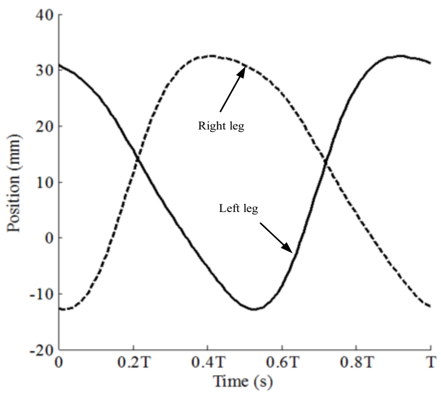

Fig. 7. Hip joints hydraulic cylinder displacement curve.

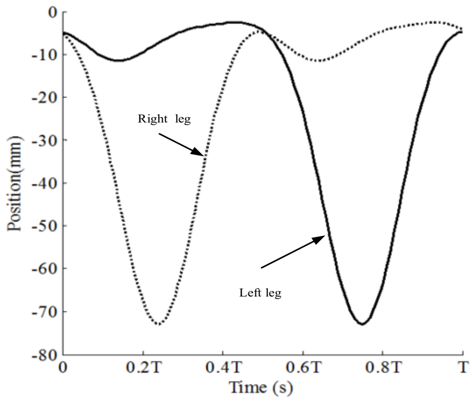

Fig. 8. Knee joint hydraulic cylinder displacement curve.

$$\begin{cases} r_{hl} = \sqrt{l_{11}^{\ 2} + l_{21}^{\ 2} - 2l_{11}l_{21}\cos(\theta_1(\mathrm{t}) + 90^\circ)} - l_{01} \\ r_{hr} = \sqrt{l_{11}^{\ 2} + l_{21}^{\ 2} - 2l_{11}l_{21}\cos(\theta_1(\mathrm{t} - 0.4T) + 90^\circ)} - l_{02} \\ r_{kl} = \sqrt{l_{12}^{\ 2} + l_{22}^{\ 2} - 2l_{12}l_{22}\cos(180^\circ - \theta_2(\mathrm{t}))} - l_{03} \\ r_{kr} = \sqrt{l_{12}^{\ 2} + l_{22}^{\ 2} - 2l_{12}l_{22}\cos(180^\circ - \theta_2(\mathrm{t} - 0.4T))} - l_{04} \end{cases} \tag{12}$$

The leg cylinder displacement curves are shown in Figures 7 and 8.

4.2. Dynamics of lower limb rehabilitation robot

The Lagrange dynamics modeling approach was used to analyze the simplified model of the human lower limb.

l_1 was the length of the thigh, l_2 was the length of the leg. θ_1 was the thigh (hip) angle in the sagittal plane, and θ_2 was the leg (knee) angle in the sagittal plane. The following are the dynamics calculations.

Kinetic energy of the thigh was found with the following:

$$E_{K1} = \frac{1}{6} M_{thigh} l_1^2 \dot{\theta}_1^2 \tag{13}$$

The centroid of the calf is the calf midpoint. Its coordinates in the coordinate system for the centroid position were as follow:

$$\begin{cases} x_2 = l_1 \sin\theta_1 + r\sin(\theta_1 - \theta_2) \\ \mathrm{y}_2 = l_1 \cos\theta_1 + r\cos(\theta_1 - \theta_2) \end{cases} \tag{14}$$

The total kinetic energy of the system was obtained with the following:

$$
\begin{aligned}
E_{k2} &= E_{K1} + E'_{K2} + E''_{K2} \\
&= \frac{1}{6} M_{thigh} l_1^2 \dot{\theta}_1^2 + \frac{1}{2} M_{shank} \left[l_1 \dot{\theta}_1^2 + 2 l_1 r \dot{\theta}_1 \left(\dot{\theta}_1 - \dot{\theta}_2 \right) \cos\theta_2 + r^2 \left(\dot{\theta}_1 - \dot{\theta}_2 \right)^2 \right] + \frac{1}{24} M_{shank} l_2^2 \dot{\theta}_2^2
\end{aligned} \tag{15}
$$

According to the Lagrange equation:

$$
f_i = \frac{d}{dt}\left(\frac{\partial E_K}{\partial \dot{q}_i} \right) - \frac{\partial E_K}{\partial q_i} + \frac{\partial E_p}{\partial q_i} \tag{16}
$$

The following shows it written in matrix form:

$$
\begin{aligned}
\begin{bmatrix} \tau_{hip} \\ \tau_{knee} \end{bmatrix} &= \begin{bmatrix} \left(\frac{1}{3} M_{thign} l_1^2 + M_{shank} l_1^2 + M_{shank} r^2 \right) & -M_{shank} \left(l_1 r \cos\theta_2 - r^2 \right) \\ -M_{shank} \left(l_1 r \cos\theta_2 + r^2 \right) & \frac{4}{3} M_{shank} r^2 \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} \\
&+ \begin{bmatrix} M_{shank} l_1 r \sin\theta_2 \dot{\theta}_2^2 \\ M_{shank} l_1 r \left(\cos\theta_2 - \sin\theta_2 \right) \dot{\theta}_1 \dot{\theta}_2 \end{bmatrix} \\
&+ \begin{bmatrix} (-\frac{1}{2} M_{thign} g l_1 + M_{shank} g l_1) \sin\theta_1 + M_{shank} g r \sin\left(\theta_1 - \theta_2 \right) \\ M_{shank} g r \sin(\theta_1 - \theta_2) \end{bmatrix}
\end{aligned} \tag{17}
$$

5. Conclusion

Four kinds of fitting curves were compared, and the Fourier fitting curve was selected for fitting the CGA data. The functional relation between angle, height, step size, and gait cycle was calculated by the verse and inverse kinematics analysis. The function was significant for the commonality of the lower limb rehabilitation robot.

The lower limb rehabilitation robot can be seen as a series robot. The angular velocity and angular acceleration during the robot's motion were calculated through kinematics analysis. The moment of force and the force of the hydraulic cylinder were calculated through dynamics analysis. The Lagrange dynamics modeling approach was used in this article to build the dynamical model.

A rehabilitation robot was designed to achieve rehabilitation in patients. The robot was able to operate with patients of different height and weight. Patients of different muscle strength were also able to use the robot because it possessed a dynamical weight loss device. Moreover, the problem of trajectories of different people was also solved.

Acknowledgments

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