Development of a New Lower Limb Rehabilitation Robot for Bedside Training

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Abstract. With the development of aging society, a great number of stroke patients are rapidly increasing. To meet the rehabilitation training needs of stroke patients, this paper proposed a simple, reliable and universally applicable lower limb rehabilitation training robot based on human lower limb movement characteristics. The robot is mainly composed of trolley, electric lifting column, screw adjustment component and left and right training mechanism. The kinematic model was developed by the D-H parameters method. Based on the rehabilitation mechanism, two modes of active training and passive training were designed. The robot can replace the work of therapists, significantly reduce the workload of therapists, and effectively alleviate the social situation of therapist shortage.

Keywords. Rehabilitation training robot; structural design; kinematics.

1. Introduction
With the acceleration of the aging problem, the national health issue has attracted the attention of the society and the country. The number of stroke patients is increasing every year in China. Due to the current situation of shortage of rehabilitation therapists, most of the hemiplegic patients do not receive effective treatment at an early clinical stage, which makes the patients’ conditions worsen and seriously affects their lives. Traditional rehabilitation training does not guarantee that patients can complete the rehabilitation training according to the set movement trajectory every time, which is not only inefficient but also poorly quantifiable [1].

Domestic and foreign experts and scholars have carried out the research of lower limb rehabilitation robot. The robot suit HAL developed by Atsushi Tsukahara of the University of Tsukuba, Japan, could help complete paraplegics achieve sitting-standing transition of the lower limbs for rehabilitation [2]. However, the rehabilitation robot had a single function and could not be adapted to most patients. The Kine Assis, developed at the University of Chicago, had a treadmill underneath the patient’s foot, which drove the patient to walk through the movement of the treadmill, but the training mode of this rehabilitation robot was single and large, which made complex rehabilitation training difficult to achieve [3]. The University of Delaware had been developed ALEX II, a lower extremity exoskeleton rehabilitation robot with 19 degrees of freedom that better met the requirements of the human body’s
individual joint degrees of freedom. It is noted that the number of degrees of freedom greatly increases the difficulty of the control algorithm [4]. Zhejiang University developed wearable lower limb-assisted exoskeleton robot [5], which was only suitable for patients with the ability to stand and could not be trained for bedridden patients.

In this paper, a lower limb rehabilitation training robot was designed as shown in figure 1. This rehabilitation robot made up for the deficiencies of existing training devices and solved the problems of bedridden patients’ difficulty in getting effective training and low training accuracy. The rehabilitation robot was designed as an equal-length two-link mechanism, while a synchronous pulley was installed on the linkage to realize the way of driving multiple degrees of freedom by a single motor. The principle was to drive the robot arm to work in a coordinated manner according to a prescribed path by controlling the motor to drive the patient’s lower limb for rehabilitation training. The bedside lower limb rehabilitation robot can reduce the burden of therapists and provide scientific and effective training mode to achieve better rehabilitation effect.

![Figure 1. Scheme design.](image1)

![Figure 2. Human lower limb model.](image2)

The remainder of this paper was to analyze the physiological model of human lower limbs. Secondly, the structural design of beside lower limbs was designed. Thirdly, the kinematic analysis is presented. The last part was the summary and introduction.

2. The Design Requirements of Beside Lower Limbs

The human lower extremity bones are composed of the hip, knee and ankle joints as well as the thigh bone, calf bone and foot according to human physiological anatomy [6] as shown in figure 2. The movement of the human lower limbs is the rotation of the bones around the corresponding joints.

During rehabilitation training, the angle, angular velocity and angular acceleration of the hip, knee and ankle joints are changing, and the range of angular change of each joint should be within the range of joint motion, otherwise it will cause sports injury for the patient’s lower limbs. The motion angles of the joints of the human lower limbs focus on the sagittal plane as shown in table 1 [7].

| No. | Name of joint | Range of motion |
|-----|---------------|-----------------|
| 1   | hip joint     | -40°~145°       |
| 2   | knee joint    | 35°~180°        |
| 3   | ankle joint   | -30°~50°        |

Because of the differences in the human body, the specific parameters of the patient’s leg should be taken into account. The concrete dimensions of the human body of Chinese adults can be acquired by GB 10000-88, and the height of Chinese male adults is about 1678mm~1754mm. In order to improve applicability and reliability of mechanism movement, the height of 1754 mm, a thigh length of 496 mm and a calf length of 396 mm can be as the corresponding mechanism size design reference.
To meet clinical requirements, the lower limb rehabilitation robot must meet several conditions: (1) Ensuring patient safety and avoiding secondary injuries. (2) The mechanical structure should be as simple as possible to reduce the working noise. (3) Patient data can be collected during training, which can assess the effectiveness of their rehabilitation.

3. Design of Lower Limb Rehabilitation Robot

3.1. The Determination of Structural Scheme

The research shows that flexion and extension of the legs can drive the ankle and hip movements, which can increase venous return pressure[8], accelerate the recovery of the patient’s leg function and make the stiff leg muscles to become flexible[9]. In order to achieve horizontal round-trip movement, the equal-length two-link mechanism is used and the timing pulley is installed on the linkage, which can achieve multiple degrees of freedom driven by a single motor. The overall scheme is shown in figure 3.

![Diagram of rehabilitation training](image1)

**Figure 3.** Diagram of rehabilitation training.

3.2. The Determination of the Size of the Mechanism

A sketch of the rehabilitation training structure (unilateral) is shown in figure 4. The length of the lower leg LCD and the thigh LDF is 396 mm and 496 mm, respectively, and the minimum angle of knee movement $\beta$ is 35° when the training is in the limit of knee flexion. LCF can be found by the cosine theorem in equation (1).

$$L_{CF}^2 = L_{CD}^2 + L_{DF}^2 - 2L_{CD}L_{DF} \cos \beta$$  \hspace{1cm} (1)

$\beta$ is 180 degrees while the training is at the limit of knee extension, then, the difference between the LCF of knee extension and knee flexion is equal to 606 mm when LCF is 892mm. If the initial angle is
60°, the design size of the rotating arm should be 606 mm to reach the limit position of the knee joint during training. In actual rehabilitation training, since the extreme position of the knee joint is rarely trained, the value of the initial angle $\alpha$ can be adjusted appropriately to achieve training at any angle within the range of motion of the knee joint.

3.3. The Structure of Overall Design

The overall design of the bedside lower limb rehabilitation robot is shown in figure 5. It mainly consists of a trolley, a lifting column, a screw adjustment assembly and the same left and right training mechanisms. The design of robot enables the patient to rehabilitate the patient’s lower extremity through the left training mechanism and the right training mechanism. It also enables the training process to be optimized based on the force conditions collected by the pressure sensors set on the pedals. The robot fixed to the end of the bed is pushed by the therapist, and the patient’s foot is placed on the foot pedal via strap.

![Figure 5. Overall structure of the lower limb rehabilitation robot.](image)

The lower limb rehabilitation robot has two training modes, including active and passive. Different training modes can be selected by the size of the lower limb muscle strength [10]. Most pre-stroke patients need passive training as they have no motor ability in their lower limbs. Their lower limb movement is drove by the rotating arm by motor. In the middle and late stages of rehabilitation, the ability of the lower limbs is gradually restored. Adopting active training mode, the patient’s lower limb muscle strength overcomes motor resistance movement, and thus achieve the purpose of training. The rehabilitation robot (unilateral) has three degrees of freedom, including the horizontal direction of the X-axis, the horizontal direction of the Y-axis and the vertical direction along the Z-axis. The horizontal direction of the X-axis is the foot pedal movement by motor driving. Transmission mechanism can realize the patient’s knee extension and flexion training. The horizontal direction of the Y-axis is driven by the handwheel, which can adjust the distance to accommodate patients with different widths of pelvis to different people. The vertical direction along the Z-axis is driven by electric lifting, which can increase the strength of hip joint training in the later stage of rehabilitation and adjust the foot height properly.

3.4. The Design of Rotating Arm

In order to avoid collision between the rotating arms during the rehabilitation training, the rotating arm near the bed end was designed as an L-shape as shown in figure 6. In order to realize the lightweight design, the L-type rotating arm is made into a symmetrical structure and its middle part is connected by a fixed connector. The two ends of the L-shaped rotating arm are connected with the U-shaped rotating...
arm and the foot pedal, respectively, and the rotating arm can be rotated relative to each other. A timing pulley is installed in the U-groove of the U-shaped rotating arm. Due to the relative rotation, it makes the synchronous pulley drive the L-shaped rotating arm when the motor drives the U-shaped rotating arm to rotate.

![Figure 6. Overall design of the rotating arm.](image)

The transmission shaft I is mounted with synchronous pulley I, and the torque is transmitted to the L-shaped rotating arm via the key that threaded holes machined at both ends, and the end cover is fixed by screws to prevent the L-shaped rotating arm from axial movement as shown in figure 7.

Selecting the mass of a leg of the human body is 15kg and the force applied to the pedal is 150N when patients do rehabilitation training. The resistance training state is in the flexed knee position when the maximum torque is applied. The torque M1 of the transmission shaft I is outputted by the motor and the torque M2 is applied by the patient’s leg, and the keyway connecting two rotating arms is the dangerous surface. The stress cloud is shown in figure 8.

When the load is maximum, M1 is 123.2Nm and M2 is 61.6Nm. The maximum stress of the transmission shaft is 51.3MPa and the compression stress on the extruded surface is 8.48×10^5Pa that meet the strength requirements.

The assembly relationship of transmission shaft II is shown in figure 9. Two synchronous pulleys fixed by screws in U-shaped grooves are the synchronous rotation connected by bolts, and the two ends of the shaft are machined with threaded holes.

Transmission shaft III and synchronous pulley IV are fixed by screws, and the right end of transmission shaft III is connected to the fixed seat by screws, and the motor output shaft transmits the
torque to the U-shaped rotating arm through the key, which drives the synchronous pulley to rotate. Its rotation relationship is shown in figure 10.

![Stress cloud](image)

**Figure 8.** Stress cloud.

![Assembly relationship of transmission shaft II](image)

**Figure 9.** Assembly relationship of transmission shaft II.

![Assembly relationship of transmission shaft III](image)

**Figure 10.** Assembly relationship of transmission shaft III.
3.5. The Calculation of the Motor Power

A sketch of the rehabilitation training is shown in figure 11. Through force analysis, the motor output is the maximum power when the initial training state is the impedance training ($\alpha = 60^\circ$). The quality of human unilateral leg is about $15\, \text{kg}$, and the human lower limb applied on the force of the mechanism is $150\, \text{N}$, when the patient performs impedance training.

The bent knee is the solid line position in figure 11, and the extended knee is the dashed line position in figure 11, where point C and point E are on the same horizontal plane, the torque of point C on point A is 0 and the torque of point C on point B.

\[ T_1 = F \cdot H = 150 \times 0.606 \times \cos 30^\circ = 78.7 \, \text{Nm} \]  
(2)

It can be viewed as applying the full mass of the human lower limb to the device when a patient is rehabilitation training. The gravitational force $G_2$ of the human lower limb is $147 \, \text{N}$. It is the state of bending knees, when the mass of human lower limbs produces the maximum torque to the motor, so the distance between the force point and the motor is $606 \, \text{mm}$. Human lower limb mass imposed on the motor torque by equation (3) to calculate.

\[ T_2 = G_2 \cdot L = 147 \times 0.606 \, \text{m} = 89 \, \text{Nm} \]  
(3)

The material of the rotating arm is aluminum alloy, the density of aluminum alloy is $2.7 \times 10^3 \, \text{kg/m}^3$, and the total volume of the rotating arm is $0.005 \, \text{m}^3$. The mass of the rotating arm can be calculated by equation (4).

\[ m = \rho \cdot V = 2.7 \times 10^3 \, \text{kg/m}^3 \times 0.005 \, \text{m}^3 = 13.5 \, \text{kg} \]  
(4)

Rotating arm gravity $G_3$ is $132.3 \, \text{N}$, the distance $L_3$ between the centroid of the rotating arm and the motor is $0.303\, \text{m}$, and the torque generated by the mass of the rotating arm can be calculated by equation (5).

\[ T_3 = G_3 \cdot L_3 = 132.2 \times 0.303 \, \text{m} = 40 \, \text{Nm} \]  
(5)

The total torque generated is completely offset by the torque generated by the motor, so the output torque generated by motor can be calculated by equation (6).

\[ T = T_1 + T_2 + T_3 = 78.7 \, \text{Nm} + 89 \, \text{Nm} + 40 \, \text{Nm} = 207.7 \, \text{Nm} \]  
(6)

During rehabilitation, the frequency of knee flexion and extension can be adjusted according to the patient’s rehabilitation effect. The rotating arm is in the limit position when Frequency of knee flexion and extension is 10 times/min. The required time is 3s when AB is from $0^\circ$ to $90^\circ$, and the angular velocity of AB can be calculated by equation (7).

\[ \omega = 30^\circ \times \pi / 180 \, \text{rad/s} = 0.52 \, \text{rad/s} \]  
(7)

The power of the motor can be calculated by equation (8):

\[ P = T \cdot \omega = 207.7 \, \text{Nm} \times 30^\circ \times \pi / 180 \, \text{rad/s} = 108.7 \, \text{W} \]  
(8)
Considering the 1.5 times safety margin, the output power of motor is 163.1W. Techservo MT series brushless DC motor ST10N60P20V2EX for 200W motor is chosen. The output torque of the motor is 0.637Nm, and the rated speed is 3000rpm.

4. Kinematic Analysis and Simulation

4.1. Establishing Kinematic Equations

Using the D-H description method [11], its equivalent D-H parametric model can be obtained as shown in figure 12.

The D-H parameters of each connecting rod are shown in table 2.

| link | $\theta_i$ (°) | $\alpha_i$ (°) | $L_i$ (mm) | $d_i$ (mm) |
|------|----------------|----------------|-------------|-------------|
| 1    | $\theta_1$     | 0              | $L_1$       | 0           |
| 2    | $\theta_2$     | 0              | $L_2$       | 0           |

The change of coordinates between two adjacent joints can be found by the homogeneous coordinate transformation. The homogeneous coordinate transformation matrix between two adjacent joint coordinate systems by equation (9).

$$^i_0T = \begin{bmatrix} \cos \theta_i & -\sin \theta_i \cos \alpha_i & \sin \theta_i \sin \alpha_i & L_i \cos \theta_i \\ \sin \theta_i & \cos \theta_i \cos \alpha_i & -\cos \theta_i \sin \alpha_i & L_i \sin \theta_i \\ 0 & \sin \alpha_i & \cos \alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(9)

The parameters of table 2 are brought into the equation (9) to find the homogeneous coordinate transformation matrix for each coordinate system by equations (10) and (11).

$$^i_0T = \begin{bmatrix} \cos \theta_i & -\sin \theta_i & 0 & L_i \cos \theta_i \\ \sin \theta_i & \cos \theta_i & 0 & L_i \sin \theta_i \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(10)

$$^i_0T = \begin{bmatrix} \cos \theta_1 & -\sin \theta_1 & 0 & L_1 \cos \theta_1 \\ \sin \theta_1 & \cos \theta_1 & 0 & L_1 \sin \theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(11)
Transformation matrix of the end of the rotating arm with respect to the base coordinates by equation (12).

\[ \begin{bmatrix}
    c_1 c_2 - s_1 s_2 & -c_1 s_2 - c_2 s_1 & 0 & L_1 c_1 + L_2 c_1 c_2 - L_2 s_1 s_2 \\
    c_1 s_2 + c_2 s_1 & c_1 c_2 - s_1 s_2 & 0 & L_1 s_1 + L_2 c_1 s_2 + L_2 c_2 s_1 \\
    0 & 0 & 1 & 0 \\
    0 & 0 & 0 & 1
\] 

(12)

where, \( c_1 \) represents the \( \cos \theta_1 \), \( s_1 \) represents the \( \sin \theta_1 \), \( c_2 \) represents the \( \cos \theta_2 \), \( s_2 \) represents the \( \sin \theta_2 \).

4.2. Motion Simulation Analysis

Using solidworks to build a model and perform motion simulation analysis, the motion of the end of the mechanism can be visualized in the animation of the model. The patient performs a knee flexion and extension training is 6s when the frequency of training is 10 times a minute. Patients underwent passive training with a simulation time of 6s. The speed curve and acceleration curve at the end of the mechanism are shown in figure 13.

![Figure 13. The speed and acceleration curve of the end of the mechanism.](image)

The end of the mechanism moves gently in the horizontal direction, with no sudden changes in acceleration, causing no discomfort to the patient’s legs as shown in figure 13.

5. Conclusion and Future Work

In this paper, a bedside lower limb rehabilitation robot has been proposed. The passive training, active training and combined training of the patient’s lower limbs were achieved without causing the secondary damage to the patient. It solved the problem of early stroke patients who could not get effective training for their lower extremities. The robot structure design was described in detail. The use of a single motor to drive multiple degrees of freedom enabled the patient’s lower limbs to do rehabilitation training on a specific trajectory. The overall structure were designed to be compact, reliable and easy to use. The robot is easier for patients to accept and use, and can effectively improve patient participation and rehabilitation effect.

Future work will refine the structural design and control system. Establishing an information collection system will enable the detection and assessment of patients’ real-time state. The rehabilitation robot will also be processed and assembled and tested to verify the effectiveness of the lower limb rehabilitation robot.
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References
[1] Bulea T C and Triolo R J 2012 Design and experimental evaluation of a vertical lift walker for sit-to-stand transition assistance Journal of Medical Devices 6 (1) 1-5.
[2] Tsukahara A, Kawanishi R, Hasegawa Y, et al. 2010 Sit-to-stand and stand-to-sit transfer support for complete paraplegic patients with robot suit HAL Advanced Robotics 24 (11) 1615-1638.
[3] Peshkin M, Brown D A, Santos-Munne J J, et al. 2016 KineAssist: A robotic over ground gait and balance training device International Conference on Rehabilitation Robotics (IEEE) pp 241-246.
[4] Winfree K N, Stegall P and Agrawal S K 2011 Design of a minimally constraining, passively supported gait training exoskeleton: ALEX II 2017 International Conference on Rehabilitation Robotics (ICORR) (IEEE) pp 1-6.
[5] Niu B 2006 Research and Implementation of Wearable Lower Limb Walking Exoskeleton Control Mechanism (Hangzhou: Zhejiang University) pp 21-28.
[6] Wu Q 2018 Research on anatomical model of lower limb musculoskeletal system Biped and Health 27 (187) 133-134.
[7] Liu X 2017 Structure design and kinematics analysis of limb rehabilitation training robot Machinery Design & Manufacture (09) 246-249.
[8] Du J, Fan Y, Li X, Sun Y, Pang W, et al. 2017 Development and clinical effect of self-made lower limb rehabilitation device for children with cerebral palsy Chinese Journal of Rehabilitation Theory and Practice 23 (04) 430-432.
[9] Oymagil A M, Hitt J K, Sugar T, et al. 2007 Control of a regenerative braking powered ankle foot orthosis IEEE International Conference on Rehabilitation Robotics pp 28-34.
[10] Zhang X, Bi X, Sun D, et al. 2018 Effects of different isokinetic training modes on the recovery of lower limb function in patients with hemiplegia after stroke Chinese Journal of Rehabilitation Medicine 33 (005) 583-585.
[11] Rocha C R, Tonetto C P and Dias A 2011 A comparison between the Denavit-Hartenberg and the screw-based methods used in kinematic modeling of robot manipulators Robotics and Computer Integrated Manufacturing 27 (4) 723-728.