Lower-Limb Rehabilitation Robot Design

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Abstract. It is a general assumption that robotics will play an important role in therapy activities within rehabilitation treatment. In the last decade, the interest in the field has grown exponentially mainly due to the initial success of the early systems and the growing demand caused by increasing numbers of stroke patients and their associate rehabilitation costs. As a result, robot therapy systems have been developed worldwide for training of both the upper and lower extremities. This paper investigates and proposes a lower-limb rehabilitation robot that is used to help patients with lower-limb paralysis to improve and resume physical functions. The proposed rehabilitation robot features three rotary joints forced by electric motors providing linear motions. The paper covers mechanism design and optimization, kinematics analysis, trajectory planning, wearable sensors, and the control system design. The design and control system demonstrate that the proposed rehabilitation robot is safe and reliable with the effective design and better kinematic performance.

1. Introduction
A rehabilitation robot is a robot with the application of robotic technology to the rehabilitation needs of people with disabilities as well as the growing elderly population [1]. An intelligent rehabilitation robot should be a human adaptive mechatronics (HAM) system. The HAM main aim is to introduce to a human-machine system a capability; that the machine can measure, or understand, the level of the skill of its human operator. Another HAM aim is to develop an integrated theory and technology which can adapt the HAM machine to the human according to their skill, in order to maximize not only the total performance of the human-machine system, but also to help improve the skill of the human [2]. This paper researches a human and machine interaction system—a rehabilitation robot to assist and support people with a paralysis problem. Thus, the research conducted in this paper belongs to a core part of research into HAM. The lower-limb rehabilitation robot aims to help people, who suffer paralysis caused by disease or lower-limb movement disorder following an accident, to improve and resume limb functions. According to World Health Organization (WHO) statistics, the world population of people over 60 years old will double by 2050, and the number of handicapped people from disease will increase. Thus, the requirement of the rehabilitation robots is in demand [3].

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In recent years, the research on rehabilitation robots has become a hot topic, and several rehabilitation robots have been developed. The Lokomat, developed by Hocoma AG (Volketswil Switzerland), was the first driven gait orthosis that helped to improve the walking movements of patients who are gait-impaired. Colombo et al. [4, 5] gave a detailed description of the device. Veneman et al. [6, 7] developed a gait rehabilitation device called LOPES which combined a freely translatable and twodimensional (2D)-actuated pelvis segment with a leg exoskeleton containing three actuated rotational joints (two at the hip and one at the knee). Cullell et al. [8] designed a knee-ankle-foot orthosis based on biomechanical data to restore the human gait, providing stability during the standing phase. Pennycott et al. [9] studied a body-weight supported robotic-assisted device; they presented a method of estimating and controlling the rate of active work done during supported stepping, and conducted the experimental validation through ambulation of three subjects with a spinal cord injury. Yaskawa Electric Corporation of Japan made a lower-limb rehabilitation robot, TEM LX2 type D [10], which was mainly used for patients with lower-limb disease in an acute phase. Its main purpose was to enable the patients to restore their physical functions and walking ability. Saito et al. [11] developed an orthosis externally powered by a bi-articular muscle mechanism with a bilateralservo actuator. Hunt et al. [12] investigated feedback control strategies for integration of electric motor assist and functional electrical stimulation (FES) for paraplegic cycling, and provided indicative results from one paraplegic subject where a series of feedback-control tests illustrated accurate control of cycling cadence, leg power control, and external disturbance rejection. Chen et al. [13] proposed a new prototype of lower-limb rehabilitation robots, and the prototype might give considerable protection to patients. Yeh and Yu [14] developed a lower-limb mobile training robot that provided adequate motion functions, such as the passive and resistive motions of multiple joints for increasing training performances and for shortening training programs. Beyl et al. [15] reported on the development of a gait rehabilitation exoskeleton with a knee joint powered by pleated pneumatic artificial muscles. Simon et al. [16] built a lower-limb robotic device that used a novel control strategy for increasing force symmetry during bilateral lower-limb extensions. Costa et al. [17] reported on the design and control of a new ‘human friendly’ orthosis (exoskeleton), powered by high power pneumatic muscle actuators (pMAs). Willems et al. [18] used a Biodex System 3 Dynamometer made by Biodex Medical Systems Inc. to determine the isokinetic peak torque and peak torque/body-weight values for reciprocal concentric and eccentric eversion–inversion movements of the ankle. Tsoi and Xie [19] designed a parallel ankle rehabilitation robot and investigated the potential advantage of using a variable impedance controller to perform ankle rehabilitation exercises. Saglia et al. [20] presented a redundantly actuated parallel mechanism for the ankle rehabilitation. With the advance of computer network technology and remote operation technology, remote operating robots began to be used in telemedicine, remote surgery and remote rehabilitation [21–23]. Girone et al. [24] proposed a Stewart platform based system for the ankle tele-rehabilitation.

Although researchers have developed many kinds of rehabilitation robots, there are still few intelligent rehabilitation robots that can carry out targeted rehabilitation training from the motion intention of patients. In this paper, a lower-limb rehabilitation robot used for patients with paraplegia is proposed. The rehabilitation robot is an exoskeleton rehabilitation robot with multi-joints which can realize the single joint movement of the lower-limb. In contrast to the rehabilitation robots adopting the suspension system and treadmill to realize walking training, the rehabilitation robot is mainly used for paraplegic patients whose lower-limbs cannot move. Therefore, the robot mechanisms are installed in a chair so that the patient can be trained while sitting in the chair, which is more comfortable than standing on a treadmill or suspending body using a weight-support system, and the more reasonable for the clinical rehabilitation of the paraplegia patients. Moreover, the proposed rehabilitation robot has the following design features: (1) three rotary joints; (2) wearable sensors force sensors, which can be installed easily, are used to measure the force creating by muscles, which can greatly reduce the manufacturing cost; and (3) the design takes fully into account the human lower-limb data, and the length of the connecting link can be adjusted over a certain range according to the size of the patient. This paper is organized as follows. In section 2, the mechanism design and sensors are detailed. In
section 3, modeling of sensors. In section 4, the control system and design. Finally, conclusions are presented in section 5.

2. Mechanism design and sensors

2.1. Determination of degrees of freedom
The movement of a human lower limb includes: the vast scale forward swing, small-scale back and side swing of the thigh; the vast scale back swing of the knee joint; and the foot rotation around the ankle joint in the vertical plane and horizontal plane [25]. Since the movement of the human lower limb in the sagittal plane is the basic movement form, the rehabilitation robot is designed as three degrees of freedom that can realize the movement of the hip joint, the knee joint, and the ankle joint in the sagittal plane.

According to the movement features of the human lower limb, a rehabilitation robot with three-planed links is designed and shown in figure 1. Three links are connected by three revolute joints. The revolute joint \( o_1 \) connects with link 1 and the base; the revolute joint \( o_2 \) connects with link 1 and link 2; and the revolute joint \( o_3 \) connects with link 2 and link 3.

![Figure 1. Diagram of the rehabilitation robot.](image)

2.2. Determination of link length and joint rotation range
Since the size of the lower limb differs for each patient, the length of the three links should be designed to meet the requirements of a height range from 1500mm to 1900mm. Since the lower limb length of a male is greater than that of a female, the data of a male is taken as the maximum of height, and the data of a female as the minimum of height. From reference [26], the dimension proportions of thigh, calf, and ankle relative to height are 0.471, 0.265, and 0.045, respectively for a male, and are 0.466, 0.261, and 0.042, respectively for a female. Therefore, the maximum and minimum length of the every link can be calculated as shown in table 1. In the actual design, the design length of every link should be greater than the theoretical length.

| Links | Theory length (mm) | Design length (mm) |
|-------|--------------------|--------------------|
|       | Minimum | Maximum | Minimum | Maximum |
| Thigh | 306     | 420     | 300     | 470     |
| Calf  | 328     | 410     | 320     | 430     |
| Ankle | 100     | 200     | 90      | 220     |

The joint rotation range of the rehabilitation robot should be in accordance with the motion range of the lower limb when the patient is trained sitting on a chair. Therefore, it has to be determined based on the movement angle and the movement type of the lower limb joint [25]. When the patient
sits on the chair, the motion ranges of the hip joint, the knee joint and the ankle joint are $60^0$, $110^0$, and $70^0$, respectively, which are taken as the joint rotation ranges of the rehabilitation robot.

2.3. Calculation of Joint Moments

Different types of sensors can measure force and movement of human body segments, but joint moments are difficult to directly measure by sensors as it relates to many other parameters of human body. However, joint moment is one of the most important parameters in evaluating the motor function of human limbs, and it can reflect accurately the effectiveness of rehabilitation activities. Therefore, in this paper the joint moments of hip, knee, and ankle are calculated based on the data measured by the sensor system.

\[ m_1 : \text{mass of L1} \]
\[ m_2 : \text{mass of L2} \]
\[ m_3 : \text{mass of L3} \]

Figure 2. A diagram illustrating dynamic.

As shown in figure 2, the magnitude and location of F can be acquired from GRF and COP data measured by the force plate. $\theta_1$, $\theta_2$ and $\theta_3$ can be acquired from the angle data measured by the three wearable motion sensors; L1, L2, and L3 can be acquired by the lower limb lengths of users; and m1, m2, and m3 can be estimated by the weight of users and the mass percentage law of human body. Moreover, the parameters p, q, and w are introduced to indicate the mass centre locations of foot, and shank. As all the data are real-time measured by the sensor system of the rehabilitation robot, the joint moments can be real-time calculated in the computer control program. Finally the joint moments (M) of ankle, knee and hips can be represented by the equation:

\[
M_{\text{ankle}} = Fx_1 - pL_1 m_1 g
\]
\[
M_{\text{knee}} = F[L_2 \cos \theta_1 - x_1] - qL_2 \cos \theta_1 m_2 g - [L_2 \cos \theta_1 - pL_1] m_1 g
\]
\[
M_{\text{knee}} = F[L_3 \cos \theta_2 - L_2 \cos \theta_1 + x_1] - wL_3 \cos \theta_2 m_3 g - [L_3 \cos \theta_2 - qL_2 \cos \theta_1] m_2 g - [L_3 \cos \theta_2 - L_2 \cos \theta_1 + pL_1] m_1 g
\]

3. Modeling of sensors

3.1. Modeling of IPMC sensor

An ionic polymer-metal composite (IPMC) consists of a polyelectrolyte membrane containing cat ions with a solvent and metal electrodes chemically plated on both surfaces of the membrane. The present study investigated an IPMC sensor model using a RC circuit where the electric components were related to the physical parameters of the IPMC. A charge model that describes a linear kinematic
relationship between the charge distributions and the applied bending angles was developed, and the time derivative of the charge model was implemented to the circuit model as a current source. The parameters were estimated by minimizing the error between the real output signal and the simulated output signal from the model. The effectiveness of the model was also tested using the inverse model that reproduces the input bending angles. Finally, the IPMC sensor was mounted on the surface of an upper limb to monitor the knee flexion and extension using the inverse model that was realized in an analog electric circuit using operational amplifiers [23]. Figure 3 shows the IPMC sensor used to measure the angular rotation of human shank and trunk.

![Image of coated IPMC sensor](image.png)

Figure 3. The image of coated IPMC sensor [23].

The main contribution of this paper is the development of a practical model of IPMC sensor which is easily applicable to real world. Another contribution is that the performance of the IPMC sensor is demonstrated in a real biomedical application for lower limbs Robot. The relation between the current (I) and generation and the bending angle (θ) can be obtained as

$$I = K \frac{d\theta}{dt} \tag{4}$$

![Circuit model of the IPMC sensor](image.png)

Figure 4 Circuit model of the IPMC sensor [23].
Figure 4 shows the circuit model of IPMC sensor that has the current source. The circuit model is connected to the measurement device through the resistances \( R_{e1} \) and \( R_{e2} \) acting as the resistances along the surface of the IPMC. Since the polymer membrane is sandwiched between the two electrodes, the IPMC has a capacitance (C), as shown in figure 4. \( R_c \) represents an ion diffusion resistance, and R represents the resistance of polymer [23].

Because the input buffer resistance of DAQ is much greater than the surface resistances of IPMC, the effects of \( R_{e1} \) and \( R_{e2} \) are ignored for the simplification of the model. Then, the output voltage (Vo) is written by

\[
V_0 = IZ_T
\]  

Where Laplace domain expression of \( Z_T \) is

\[
Z_T = \frac{sR_cC + R}{s(R + R_c)C + 1}
\]

After assuming all the initial conditions are zero, the governing differential equation between the input bending angle (\( \theta \)) and the output voltage (Vo) is represented by

\[
V'_0 = \frac{1}{(R + R_c)C} V_0 = \frac{KRR_c}{R + R_c} \theta' + \frac{KR}{(R + R_c)C} \theta''
\]

3.2. Modeling of force plat sensor

Force plates are commonly used in biomechanics laboratories to measure ground forces involved in the motion of human subjects. A force plate is simply a metal plate with one or more sensors attached to give an electrical output proportional to the force on the plate. The sensor can either be a strain gauge or a piezoelectric element. Figure 5 shows the architecture of a force plat sensor.

If a force is applied to the center of the plate, each piezo will share the load equally and generate the same charge. An off-center force results in an unequal sharing of the load. In commercial force plates the four piezo outputs are monitored separately and processed electronically to provide measurements of the total force as well as the line of action of the force. In the present case, all four piezos were connected directly in parallel. Each piezo generates a charge proportional to the local force on the piezo. When all four piezos are connected in parallel, the output signal is proportional to the total charge and is hence proportional to the total force on the plate. Consequently, the same signal is generated regardless of whether one stands in the middle of the plate or on one corner, provided all four piezos are closely matched in sensitivity.
The figure 6 and 7 shows where we place force plate sensor based on located forces in the foot. Two load cells are set at the location of 1 and 2 of the force plate. Based on this structure, load \( F \) can be calculated by summation. Furthermore, the data measured by the force plate can be real-time utilized in the control program.

![Located forces in the feet](image1)

Figure 6. Located forces in the feet

![Force plate sensor placed in foot](image2)

Figure 7. Force plate sensor placed in foot

4. Lower limbs robot design and control system

4.1. Lower Limbs Robot Design

Lower Limbs Robot Design (LLRD) is designed to be comfortable and safe for the patient, and adjustable. LLRD have wearable sensors which controls two types of motors, the first one creates a
movement on the knee and second on the ankle, as shown in figure 8. Figure 9 shows the relationship between the sensors and the motors in terms of control system.

4.2. Control system

To meet the needs of active, passive and assisted training, the system adopts the variable servo control modes that include position control, speed control, and current control. In active training, the method of current control is used, so that the active training of every joint can be carried out. In passive training, the method of speed and position control is used, so that the hip, knee, and ankle can be exercised according to the foot trajectory planning. In assisted training, the method of current control, based on the torque feedback and the electro-myographic signal (EMG), is used. Training effects evaluation is based on the feedback of surfaces EMG, motion measurement and force/torque measurement.
5. Conclusion
A lower-limb rehabilitation robot with the function of active training, passive training, and assisted training used for a patient with a lower-limb paralysis has been investigated and developed in this paper. The research conducted is based on the HAM concept. The developed rehabilitation robot has a mechanism where three rotary joints consist of three crank rocker mechanisms with an identical module. This feature makes the rehabilitation robot flexible enough to adapt to the variety of user needs. The values of this paper are that it covered the mechanism design, mechanism optimization, kinematics analysis, trajectory planning, motion simulation, control system, and experimental research of the rehabilitation robot. The experimental results have demonstrated that the proposed rehabilitation robot is effective, safe, and reliable and has a potential application. The mechanism developed in this paper provides a good supporting case for the HAM framework.

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