Control of a New Cycling Rehabilitation Robot Based on Fuzzy PID

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Abstract. For completing the standardized rehabilitation training of the affected limb based on the lower limb rehabilitation training robot system, it is designed that a lower limb rehabilitation robot control system based on fuzzy PID control method to realize stable and accurate control of the rehabilitation training process. First of all, this paper analyzes the ranges of motion of human hip and knees, and a single degree of freedom lower limb rehabilitation training robot system based on the belt transmission principle is designed. Then the fuzzy PID control is analyzed. And the Matlab is used to simulate the passive rehabilitation mode of the lower limb rehabilitation training robot system under different control strategies. The designed rehabilitation training test shows that the control system of the lower limb rehabilitation robot based on the fuzzy PID control method has a small speed overshoot, high control accuracy and smoother operation.

1. Introduction
With the aging of the population, the accelerated pace of life, poor lifestyles and the environment, the number of people with lower limb dysfunction caused by stroke has been increasing rapidly. According to 2018 statistics, there are 80 million stroke survivors in the world \cite{1}. Stroke is the main cause of limb disability. According to the clinical experience of the therapist to formulate a rehabilitation program for treatment is a commonly sports rehabilitation therapy, which has problems such as large staff consumption, long rehabilitation cycle, and limited rehabilitation effect. It is more and more obvious that it is difficult to look for medical services, more hospital costs and shortage of rehabilitation medical resources. The research and application of rehabilitation robot are expected to effectively alleviate the contradiction between supply and demand of rehabilitation medical resources and improve the quality of life of stroke patients.

Among many rehabilitation devices of the cycling rehabilitation robot can drive it to carry out cycling movement to achieve lower limb rehabilitation movement of stroke patients \cite{2}. Cycling exercise has recently shown positive effects on improving the function of neuromuscular system and several muscles walking ability in stroke patients \cite{3-5}. Moreover, cycling exercise has a similar kinematic pattern with walking, because both of them are cyclical and they require reciprocal flexion and extension movements of hip, knee, and ankle. Cycling rehabilitation robot can be used in early rehabilitation treatment for the integrated early rehabilitation of stroke patients \cite{6}. Functional
electrical stimulation (FES) can be used to activate the dysfunctional lower limb muscles of individuals with neurological disorders to produce cycling as a means of rehabilitation [7-8]. Kinematical and biofeedback analysis for stroke patients indicate that the cycling rehabilitation robot are effect on lower limb movement [9]. Some papers focus on the studies of the application of cycling therapies in stroke patients to identify the clinical evidence on the effectiveness of cycling therapies [2,10]. More complex control strategies are usually adopted to ensure the stability of the different lower limb rehabilitation robot system, such as hybrid force-position control, PID control, sliding mode control, impedance control, feedback-feed forward hybrid control and generalized proportional integral (GPI)[11-16].But there are few studies on the control of the cycling rehabilitation robot. The control strategy adopted by the rehabilitation robot affects the patient's rehabilitation training effect directly. In the process of cycling rehabilitation for stroke patients, the control system is nonlinear and delayed, and the lower limb rehabilitation process of the human body will lead to changes in external disturbance torque which caused by active leg force and spasm. In addition, there is a gradual disturbance to the current regulator by the disturbance of the back electromotive force and the changing load in the rehabilitation training system, so the ordinary PID control of cycling rehabilitation system is difficult to achieve accurate and stable control, and ensure the safety of the stroke patients.

According to the normal range of hip, knee and ankle flexion motion of human body, this paper presented a passive control system for lower limb rehabilitation robot which is based on fuzzy PID control. Using Matlab simulates and analyzes the uniform motion state of the lower limb rehabilitation robot. The experiment shows the dynamic diagram of the angle of the hip and knee joint of the patients with the crank rotation in the passive rehabilitation mode controlled by the ordinary PID control method and the fuzzy PID control method, respectively. The rehabilitation training experiment shows that the control based on the fuzzy PID control method has a small overshoot of the rotation speed and high control accuracy, which meets the control requirements of the passive rehabilitation mode of the lower limb rehabilitation training robot. This paper is organized as follows: In section 2, design the lower limb rehabilitation robot system. The fuzzy PID control algorithm is designed and the dynamic equation of the system is got in section 3. In section 4, it verifies the control system has obtained good control quality by computer simulation. The experimental results are discussed in section 5. Conclusions are present in section 6.

2. Design of Lower Limb Cycling Rehabilitation Robot
During the rehabilitation training of human lower limbs using lower limb rehabilitation robots, flexion is the main movement of the human lower limbs. During the hip flexion exercise, the front of the thigh is close to the torso, and the entire lower limb is in front of the coronal plane passing through the center of the hip joint. When the knee is extended, the hip can flex to 90°. When the knee is flexed, the hip can flex to more than 120°. The range of knee flexion varies depending on the position and movement of the hip joint. When the hip joint has been flexed, the active knee flexion range can reach about 140°. When the hip joint is extended, the knee joint can only flex by 150° [17]. Figure 1 shows the overall structure of the lower limb rehabilitation robot. Patients need to sit in front of the rehabilitation robot, and their feet are in contact with the crank of the lower limb of the rehabilitation robot. The synchronous toothed belt in the lower limb turning mechanism transmits the driving force of the lower limb motor to the pedal crank. During the passive movement, the motor is used as the source power to drive the lower limbs to rotate all round, completing the passive flexion rehabilitation training of the hips and knees of both lower limbs. The robot telescopic and slewing mechanism can be adjusted according to the patients' physical characteristics to adapt to the differences of different patients and ensure that the affected limb is trained on the sagittal plane during the rehabilitation process.
The passive training control system not only controls the rotational speed set by the lower limb rehabilitation training robot's turning crank output, but also adjusts its output torque in real time when the load changes. For safety, the lower limb rehabilitation training robot system is required to have better speed and acceleration performance, and the project uses a servo drive system to achieve real-time precise control. As shown in Figure 2, this system uses the industrial control integrated machine as the upper computer for connecting to the servo driver through the network communication interface and transmitting the control code to the driver. At the same time, the industrial computer and the servo driver communicate in real-time during the rehabilitation exercise. And read the drive current and speed feedback data in real-time, and the sampling frequency is set to 1KHz. The industrial computer calculates the control amount of the driving motor according to the control algorithm, the feedback signal and transmits the control amount to the servo motor drive through the network communication interface, and it is realized that the closed-loop motion control of the lower limb rehabilitation training robot finally.

![Figure 1. Lower limb cycling rehabilitation robot](image1)

3. Design of Fuzzy PID Control System
The lower limb rehabilitation training robot control system uses a servo motor to form a semi-closed loop control system, the current and velocity loop from the inside to the outside constitute a local
closed loop system. Using the feature modeling method, it is analyzed the main feature quantities of each segment of the dynamic characteristics of the passive closed-loop speed loop and current loop dual-loop system of the actual lower limb rehabilitation robot. Thus, it is obtained a state-space model representing the internal structural characteristics of a complex non-linear complex actual system. In the passive training control system based on the double closed-loop speed regulation structure, the disturbance of the load to the system is added to the actual system, that is, the relationship between the speed change and the current change are taken into account, and PID control method is used to stable system. By analyzing the dynamic performance of its passive training system, it can be known that in its actual operation, as the affected limb is driven to move periodically, the speed loop controller repeatedly switches between saturated and unsaturated states. The status of the entire system will change at any time. Aiming at such complex systems, it cannot control the system accurately and stably by using the PID control method simply. Therefore, this paper proposes to adopt a fuzzy PID algorithm to design a passive closed-loop speed regulation system for robots, that is, to adjust PID parameters online based on the fuzzy controller to make it adapt to changing system performance. Figure 3 depicts the control principle of the lower limb rehabilitation training system based on the fuzzy PID. In the Figure 3, $y_d$ is the input signal of the reference position of the crank, and $\dot{\theta}(t)$ is the output angular position signal.

$$\dot{\theta}(t) = \frac{K_u K_d K_m}{s \left( (L_s + R - K_i) (J_s - 1) - K_m C_e - K_d K_m K_s \right)}$$

Figure 3. Schematic diagram of passive training control system based on fuzzy PID control

where $y_d(t)$ is the input position command, $K_u$ is the speed loop amplification factor, $K_d$ is the speed loop feedback coefficient, $K_i$ is the current feedback coefficient, $L_s$ is the armature inductance, $R$ is the armature resistance, $K_m$ is torque coefficient of lower limb drive motor, $C_e$ is motor back EMF coefficient, and $J$ is moment of inertia equivalent to the shaft. And $J = J_m + J_s$, $J_m$ is moment of inertia of motor and transmission mechanism, $J_s$ is moment of inertia during passive rehabilitation of lower limbs, $F(t)$ is the external disturbances caused by active force of the legs, spasms and others, during the rehabilitation process, $\mu(t)$ is PID control input and output, is crank output angular velocity.

The dynamic equation of the system is given by

The main idea of the fuzzy PID controller is to realize the online adjustment of the three parameters of the PID through the fuzzy controller to make it adapt to the real-time system performance. When using the fuzzy PID algorithm to design the speed regulator in the passive training control system of the lower limb rehabilitation training robot, the changing inertia load is taken into account, so that the designed controller adjusts the system to its non-linearity and time variability. The PID parameters of the system can be adjusted according to fuzzy rules to adapt with the impact of different lower limb weights on system performance. Selected the rotational speed output mechanism of the lower limb rehabilitation training robot rotational speed deviation of crank $|E|$ and speed deviation change rate $|EC|$ as two input variables of the fuzzy controller. Proportional coefficient deviation $\Delta K_p$, integral coefficient deviation $\Delta K_i$, and differential coefficient deviation $\Delta K_d$ are the output variables of fuzzy controller. Thus, the system PID parameters are modified. In the design of the fuzzy controller, the
input and output variables of the fuzzy control domain are used to locate the seven states, recorded as \{NB, NM, NS, ZO, PS, PM, PB\}, which are negative large, negative middle, negative small, zero, positive small, positive middle and positive large, respectively. The universe of input variables \(|E|\) and \(|EC|\) are \{-3, -2, -1, 0, 1, 2, 3\}. The domains of output variables \(\Delta K_p\), \(\Delta K_i\) and \(\Delta K_d\) can be given by
\[
\Delta K_p = \{-0.3, -0.2, -0.1, 0, 0.1, 0.2, 0.3\}; \\
\Delta K_i = \{-0.06, -0.04, -0.02, 0, 0.02, 0.04, 0.06\}; \\
\Delta K_d = \{-3, -2, -1, 0, 1, 2, 3\}.
\]

4. Computer Simulation for Control System

The step signal amplitude is taken 60r/min by the test training speed. The system output is the passive training speed of the lower limb rehabilitation trainer. However, the simulation of the system based on this method only proved the effectiveness of the fuzzy PID controller used by the lower limb rehabilitation training robot for patients with the same lower limb weight during training. In order to verified whether the speed regulator designed based on the fuzzy PID method can effectively self-tune PID parameters to adapt to changes in system parameters when training patients with different weights, then control the motor to adjust the rotation speed of the rotary handle effectively. According to the investigation of human lower limb weight, the values range from 0 to 100kg, and the transfer function is established. Using Matlab to simulate and verify the passive training motion control system of the designed lower limb rehabilitation training robot. The result is shown in Figure 4.

![Figure 4](attachment:image.png)

Figure 4. Three-dimensional simulation diagram of two control methods

It can be seen from Figure 4(a), with the weight of the leg increases, the speed overshoot increases gradually, and the maximum overshoot reaches 10%, which based on PID adjustment. When designing the control system of the lower limb rehabilitation training robot for the control system, it is required that the speed overshoot of the robot cannot be too large. Otherwise, it will not only cause secondary harm to the patient, but also it will be difficult to achieve the desired rehabilitation training effect. The simulation results show that if the PID control method is used to train the passive training control system of the lower limb rehabilitation robot, it is difficult to achieve the control accuracy. Figure 4(b) shows a simulation diagram of the passive training control system of a lower limb rehabilitation training robot based on the fuzzy PID control method. As can be seen in Figure 4, with the weight of the externally loaded leg increases, the speed controller based on the fuzzy PID algorithm can adjust the PID parameters, and its maximum speed overshoot is 0.52%. This meets the
control requirements of the passive training control system of lower limb rehabilitation training robots and obtained good control quality.

5. Experiments

In order to further verify the effectiveness of the lower limb rehabilitation training robot, a test was performed on the lower limb rehabilitation robot for the fuzzy PID control method. As shown in Figure 5, there are the complete prototype system of lower limb rehabilitation robot and rehabilitation training test. The test consists of a computer system, a Kinect 2.0 body sensor, and a lower limb rehabilitation robot. Figure 6 shows the 90° sampling map of knee and hip joints.

![Figure 5](image1.png)

(a) composition diagram of experimental system  (b) passive rehabilitation mode control interface

**Figure 5.** Demonstration of passive rehabilitation process:

![Figure 6](image2.png)

**Figure 6.** 90° Sampling map of knee and hip joints

The dotted lines in Figure 7 shows the results of the angle change when the hip and knee joints move at a constant speed with the rotating crank in the Matlab simulation state. The solid line is the real time acquisition of the angle results of the hip and knee joints moving at a constant speed with the turning crank during the passive rehabilitation of the lower limbs through the Kinect 2.0 body sensor in real time. Experiments show that the lower limb rehabilitation training robot system based on fuzzy PID control method has better stable and accurate control. This system conforms the expected design requirements.
6. Conclusion
This paper combines rehabilitation medicine and ergonomics to analyze the range of motion of the human hip and knee joints during flexion exercises. On this basis, a lower limb rehabilitation robot control system based on fuzzy PID control method is designed to achieve stable and accurate passive rehabilitation training process control. The derivation process of the fuzzy PID control algorithm was analyzed, and Matlab was used to simulate the passive rehabilitation mode of the lower limb rehabilitation training robot system using different control strategies. The experiments show that the control system of the lower limb rehabilitation robot based on the fuzzy PID control method has a small overshoot of the rotation speed and high control accuracy, which can meet the needs of passive rehabilitation training for patients with different degrees and rehabilitation progress.

Future work will further study the robot-assisted patient active training effect evaluation system based on this research, and provide a basis for rehabilitation training strategies.

7. References
[1] Kurmashev S, Ospanov S, et al, Flexibility in Upper Limb Rehabilitation With the Use of 1-DOF Fourbar Linkages, Mechanisms & Robotics, 2018.
[2] Simona F, Emilia A, et al, A biofeedback cycling training to improve locomotion—a case series study based on gait pattern classification of 153 chronic stroke patients, Journal of Neuro Engineering and Rehabilitation, 2011.
[3] Mi-joung L, Sharon L, et al, Comparison of Effect of Aerobic Cycle Training and Progressive Resistance Training on Walking Ability After Stroke: A Randomized Sham Exercise–Controlled Study, Journal of the American Geriatrics Society, 2008.
[4] Yang HC, LeeCL, et al, Effect of biofeedback cycling training on functional recovery and walking ability of lower extremity in patients with stroke, Kaohsiung Journal of Medical Sciences, Vol.30, 35-42, 2014.
[5] Seki K, Sato M, et al, Increase of Muscle Activities in Hemiplegic Lower Extremity During Driving a Cycling Wheelchair, Tohoku Journal of Experimental Medicine, 2009, Vol.12, 129-138.
[6] Prokazova PR, Piradov MA, et al, Robot-assisted therapy using the MOTOmed letto 2 for the integrated early rehabilitation of stroke patients admitted to the intensive care unit, Human Physiology, 2016, Vol.42, 885–890.
[7] Emilia A, Simona F, et al, Cycling induced by electrical stimulation improves muscle activation and symmetry during pedaling in hemiparetic patients, IEEE transactions on neural systems & rehabilitation engineering a publication of the IEEE engineering in medicine & biology society, 2012, Vol.20, 320-330.
[8] Peri E, Guanziniori E, et al, Functional Electrical Stimulation and Its Use During Cycling for the Rehabilitation of Individuals with Stroke, Advanced Technologies for the Rehabilitation of Gait and Balance Disorders, 2018.
[9] Chen HY, Chen SC, et al, Kinesiological and kinematical analysis for stroke subjects with asymmetrical cycling movement patterns, Journal of Electromyography and Kinesiology, 2006, Vol.15, 587-595.

[10] Kamps A, Schüle K, Cyclic movement training of the lower limb in stroke rehabilitation, Neurologie and rehabilitation, 2005, Vol.11, 143-148.

[11] Michnik A, Brandt J, et al, Control System of the Lower Limb Rehabilitation Robot, Third International Conference on Information Technologies in Biomedicine, 2012.

[12] Bernhardt M, Frey M, et al, Hybrid force-position control yields cooperative behaviour of the rehabilitation robot LOKOMAT, Rehabilitation Robotics, ICORR 2005. 9th International Conference on, IEEE, 2005.

[13] Wang L, Zhu H, et al, Modeling and control of ankle rehabilitation robot with nonlinear factors, IEEE International Conference on Information & Automation. IEEE, 2014.

[14] Brizuela, Jorge A, Robust control of a hip-joint rehabilitation robot, Biomedical Signal Processing & Control, 2017.

[15] Azcaray Héctor, Blanco Andrés, et al, Robust GPI Control of a New Parallel Rehabilitation Robot of Lower Extremities, International Journal of Control Automation & Systems, 2018.

[16] Asl HJ, Narikiyo T, et al, Neural network-based bounded control of robotic exoskeletons without velocity measurements, Control Engineering Practice, 2018, Vol.80, 94-104.

[17] Donald AN, Kinesiology of the Musculoskeletal System: Foundations for Rehabilitation. People’s Military Medical Press: Beijing, China, 2014, pp.648–649.