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Design and Control of Lower Limb Rehabilitation Exoskeleton Based on Simulink

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Abstract: *To support the research of walking assistance and rehabilitation equipment for elderly stroke patients, a lower limb rehabilitation exoskeleton robot structure is designed to address the degree of freedom and joint layout difficulties in current serial humanoid lower limb rehabilitation exoskeletons. A simulation model was built using Matlab/Simulink and auxiliary plugins, with corresponding PID and fuzzy PID controllers designed and dynamic tuning of PID parameters carried out. To evaluate the controller's anti-interference performance more accurately, a method for simulating patient spasticity as an evaluation experiment was proposed. The performance of the controller under two different assessment methods was compared and analyzed, showing that assessing through simulated patient spasticity can better stimulate the adaptive ability of the controller, which analyzes its protective effect on patients and helps optimize the control algorithm design and performance evaluation of lower limb rehabilitation exoskeletons.*

Keywords: *stroke; movement rehabilitation; lower limb rehabilitation exoskeleton robot; fuzzy PID control; Simulink; control system simulation; performance evaluation*

1. Introduction

With the acceleration of aging population in China, stroke has become one of the diseases that seriously affect the health of elderly people. Especially for patients in spastic period, the spastic symptoms have a great impact on their walking ability and quality of life. Clinical experiments show that lower limb rehabilitation exoskeleton robots can effectively improve the rehabilitation effect of patients with lower limb motor function impairment[1].

Currently, the study of lower limb rehabilitation exoskeleton robots mainly adopts anthropomorphic configuration, which usually has hip joint, knee joint and ankle joint. The early design adopted a single degree of freedom structure, such as the American NUSTEP rehabilitation robot, the German THERA-Vital intelligent rehabilitation training device[2] and other two products. These devices are widely used due to their simple structure and low cost, but they lack comfort. In subsequent development, the structural design of rehabilitation exoskeletons is more focused on wearability, comfort and flexibility. For example, in the structure of Japan's Hybrid Assistive Leg (HAL)[3], except for the hip joint with three degrees of freedom, the other two joints have one degree of freedom each, and only drive the flexion/extension freedom of the knee joint and hip joint, while others are passive freedoms. Representative products also include the eLEGS[4] developed by the American Berkeley Bionics company and the ReWalk from Israel[5]. In addition to the anthropomorphic configuration, Honda's Ikeuchi and others have developed a non-anthropomorphic walking aid from the perspective of reducing the support reaction force of the wearer's foot sole[6]. Domestic research has made a series of achievements in this field in recent years, such as the new hybrid wearable lower limb exoskeleton robot at Shanghai Jiaotong University[7], using parallel leg type, designed a total of 12 degrees of freedom, but without knee joint; QEPLEX[8] developed by Southeast University, designed a total of 8 degrees of freedom for one leg, with 4 degrees of freedom for the ankle joint, to meet the requirements of human movement in terms of foot guidance and balance. Joint layout, degree of freedom setting, configuration design and active degree of freedom allocation are currently the difficulties of research. For serial anthropomorphic exoskeleton configuration, too many degrees of freedom will increase control difficulty and reduce smoothness of motion; while too few degrees of freedom will cause interference during human-machine interaction, thus achieving the desired gait training effect is difficult.

Currently, the control strategy of domestic exoskeletons is mostly based on traditional PID control

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theory, such as Beijing University of Aeronautics and Astronautics[9], Guangxi University[10], etc. And trajectory tracking algorithms designed on the basis of traditional PID, such as bangbang-PD algorithm in Taiyuan University of Technology[11]. Although traditional PID control has shown good performance in some simulations and tests, it is difficult to adapt to its complexity and variability due to the complex lower limb gait curve and frequent external interference. Fuzzy PID control, as an improved control method, has shown better adaptability and robustness in some research, such as Guangxi University of Science and Technology[12].

This paper compares two control methods through experiments. The current simulation experiment mainly evaluates its ability to track the gait, while simulating external interference with noise, sinusoidal signals, etc. to evaluate the controller's anti-interference performance. Lower-limb exoskeletons have different usage environments and conditions, so they have different performance requirements for controllers. Therefore, it is difficult to accurately assess their anti-interference performance under clinical situations only by interference from noise signals.

This paper designs a 5-degree-of-freedom lower limb rehabilitation exoskeleton robot structure based on the existing design difficulties, combined with patient needs and characteristics of human lower limb joints. The three degrees of freedom of hip joint are decomposed to provide reference for the allocation of joints and degrees of freedom of the lower limb rehabilitation exoskeleton robot. At the same time, based on Simulink, the PID and fuzzy PID controllers of the above model were designed, and simulation analysis was carried out; it is proposed that the controller's anti-interference ability can be evaluated by simulating the patient's spasm method, and noise interference is designed as a contrast. This paper compares and analyzes the differences in anti-interference performance between the two controllers under different evaluation methods.

2. Design of the Structure for the Lower Limb Exoskeleton Rehabilitation Robot 2

A lower limb exoskeleton rehabilitation robot is a wearable robotic device that can assist, enhance or restore the function of the lower limbs to help individuals with mobility difficulties or limited mobility walk, stand and perform other daily activities. To achieve goals such as reducing the burden on the patient, improving their quality of life and assisting in rehabilitation training, structural design should be based on the analysis of human lower limb movement to ensure safety, comfort and coordination of motion.

This section first analyzes the design requirements of the lower limb movement composition, and then carries out the overall structure size design of the lower limb exoskeleton rehabilitation robot, and uses three-dimensional software to model.

2.1 Design Requirements for the Lower Limb Exoskeleton

2.1.1 The Structure and Function Analysis of the Lower Limb Skeletal System

The lower limbs of the human body rely on joints formed by bone connections as the center of movement, mainly including three major joints: hip joint, knee joint and ankle joint. The hip joint supports actions such as walking and running, allowing for a wide range of movements. The knee joint performs flexion and extension movements, while the ankle joint realizes foot movements and stability support.

According to Figure 1 (right), each joint is not strictly rotating around the center of the ball. Therefore, a small amount of sliding can be ignored and simplified as a spherical joint. The coordinate system of the human body is set based on the positioning method in clinical medicine as Figure 1 (left), including coronal Frontal, sagittal Sagittal, and transverse Transverse. Subsequently, the spherical rotation of the simplified joint is decomposed into rotations perpendicular to three reference axes, named extension/bending, abduction/adduction, and inward/outward rotation[13].

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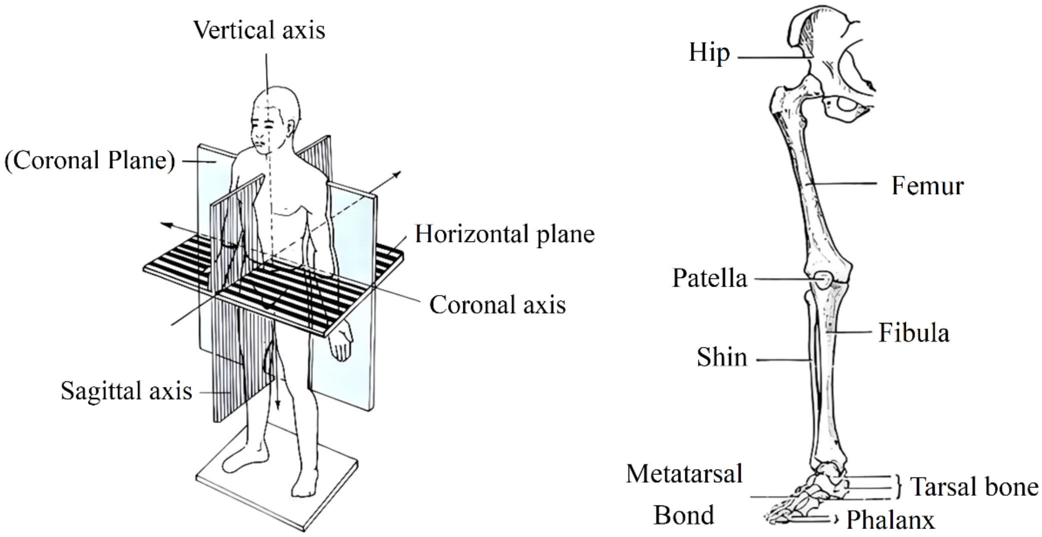

Figure 1: A diagrammatic representation of the human body structure (left) and a view of the human lower limb joints (right)[13]

Of the three joints, both hip and ankle contain three degrees of freedom while knee only contains one degree of freedom, which can only bend/stretch. At the same time, due to the restriction of ligaments, there is a large difference in the range of motion between different joints[14]. The following are the angle ranges for the lower limb joints are shown in Table 1.

Table 1: Reference Range of Joint Angles in the Lower Extremity.

Joint	Flexion/Extension	Adduction/Abduction	Internal Rotation/ External Rotation
Hip joint	-15° to 125°	-20° to 45°	-45° to 45°
Knee joint	0° to 130°	0	-15° to 30°
Ankle joint	-20° to 45°	-35° to 25°	-35° to 25°

2.1.2 Design Requirements for the Lower Extremity Exoskeleton Rehabilitation Robot

The lower limb exoskeleton rehabilitation robot is designed to assist patients in rehabilitation training and daily activities, requiring high degree of fitting with the human body without interfering with human-machine movement. The flexibility of the mechanism, comfort when worn, and high level of synergy between humans and machines are core elements for the design of the exoskeleton robot[14]. Therefore, the following requirements should be prioritized for the lower limb exoskeleton:

(1) Adaptive design for wearing: The structure should have adjustable modules, such as length and width, to accommodate the needs of patients with different body types.

(2) Anthropomorphic configuration design. Anthropomorphic design refers to the production of a product based on the external structure and movement habits of human beings and reduce the dependence on external operations outside daily behavior[15]. Use disk-shaped motor joints to match the exoskeleton joint with the human body movement joint, reduce interference and transmit auxiliary torque[16].

(3) Mechanical protection design. In the early stage of rehabilitation treatment, patients' lower limb strength is not enough to fully support their own weight and control joints, which may result in external rotation or internal rotation during movement[17]. Limitations should be added at all joints to prevent secondary injuries, and elastic structures should be designed to create passive degrees of freedom while discarding unnecessary ones.

2.2 Structure Design of Lower Limb Exoskeleton Rehabilitation Robot

In the design of a lower limb exoskeleton rehabilitation robot, only three degrees of freedom are reserved for the hip joint. The knee and ankle joints are designed with only one degree of freedom. It is

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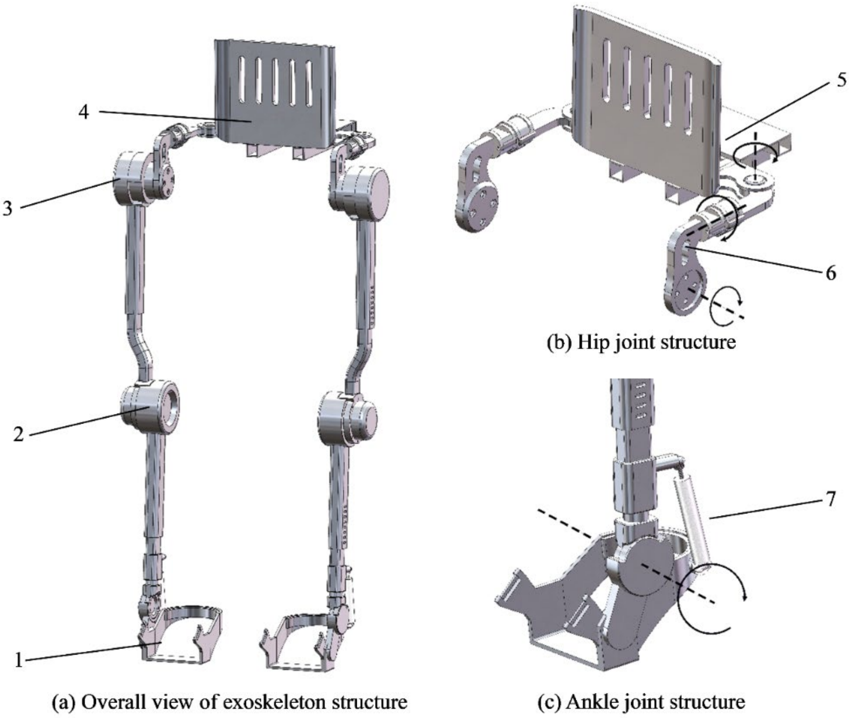
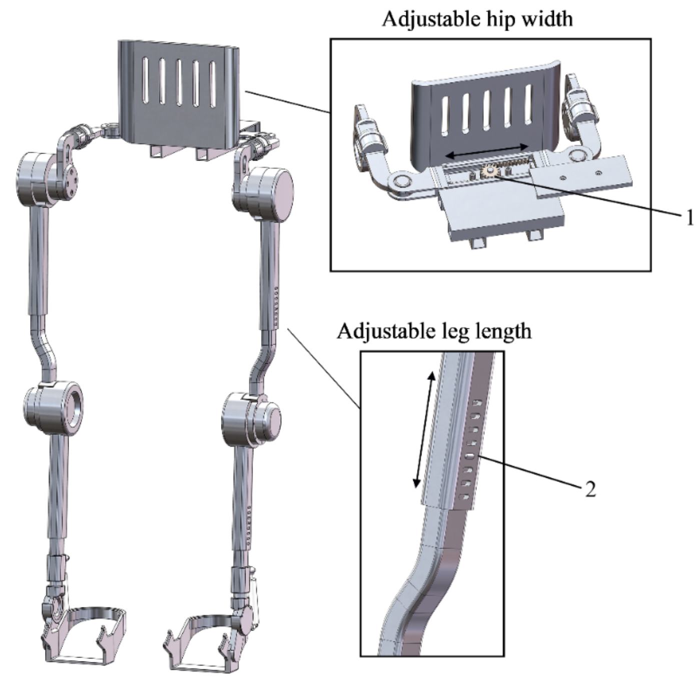
driven by disc motors and fixed by elastic belts as shown in the Figure 2.



1. Foot 2. Knee joint 3. Hip joint 4. Back plate 5. Backpack base 6. Hip support 7. Ankle elastic element

Figure 2: Design of the Lower Limb Exoskeleton Structure



1. Double gear rack adjustment mechanism 2. Spring clip position fixed

Figure 3: Adjustable structure

2.2.1 Hip Joint Design

(1) Bend/stretch as an active degree of freedom is controlled by a motor, while the other two degrees of freedom have a smaller range and influence, so they are designed with passive degrees of freedom to reduce the difficulty of intervention and control.

(2) The hip joint, as shown in Figure 2 (b), has the inner/outer rotation pivot shifted to the middle of the waist bar and the inner/outer rotation axis shifted to the back fixed frame. This increases the torque transmission effect and stability. The outer skeleton's inner/outer rotation axis does not overlap with that of the human hip joint, which can limit the range of motion of inner/outer rotation and prevent the occurrence of external/flexion during movement, thereby preventing unbalanced movements.

2.2.2 Ankles Joint Design

As shown in Figure 2 (c), the ankle joint is only designed with a single degree of freedom for bending and stretching, which can prevent external and internal rotation. The main force affecting the movement of the ankle joint is the ground reaction force during walking. Therefore, by connecting the foot component to the shank component through bidirectional composite elastic elements, the bending and stretching design of the ankle joint is designed as a passive degree of freedom, so as to reduce the interference on the wearer's movement while providing cushioning and assistance, thereby reducing the load on the ankle joint movement.

2.2.3 Integrated Design

(1) Adjustable structure of lower limbs. As shown in Figure 3, the adjustable structure of the lower limb includes three parts: the thigh, the calf and the back support. Referring to "Chinese Adult Body Dimensions" (GB-10000 88)[18], which is shown in Table 2,the lower limb dimensions data of Chinese adults are 18 J, and the preliminary design is to adjust the hip width range for wearing exoskeletons from 300 ~ 360 mm, the length range of the thigh from 410 ~ 500 mm, and the length range of the calf from 310 ~ 400 mm. This design can be applied to more than 85% of patients.

Table 2: Main dimensions of human body parts

Percentile	**5**	**10**	**50**	**90**	**95**
Thigh length (male/female)	424	434	469	506	517
	395	406	441	476	487
Calf length (male/female)	336	345	374	405	415
	311	318	345	375	384
Hip width (male/female)	303	309	334	359	367
	293	299	323	349	358

Adaptive design includes:

1) The thigh and calf use sliding joints composed of nested rectangular tubes, with nine 10 mm spacing locating holes to allow elastic clamping for length adjustment.

2) The hip support structure in Figure 3 is connected to the fixed gear with two parallel racks, and the gears are fixed on the back plate. The lower limb structures on both sides slide into the sliding groove of the back plate through the racks on the bracket so as to achieve continuous adjustment of width. The gears can be rotated by a bottom knob to make the two racks slide in parallel in the slot for continuous adjustment, with a range of 60 mm.

(2) In order to prevent secondary injury of patients during rehabilitation training, corresponding limiting devices are designed at each joint according to the normal range of motion of human lower limb joints. The movement of the joint is limited within a safe range to prevent over-steering caused by motor control and unexpected falls, etc., which may lead to secondary injury due to excessive rotation of the joint.

3. Controller Design and Simulation 3

3.1 Simulation System Construction of Simulink

In traditional PID control, once the parameters Kp, Ki and Ka are set, they cannot be changed during rehabilitation training. This makes it difficult to meet the requirements of precise control. The use of fuzzy controllers for self-tuning these three parameters can effectively solve this problem. The input is

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the error e between the desired crank speed and actual speed, as well as its rate of change ec, and the output is the correction parameter of the PID controller.

To establish a fuzzy PID controller, the first step is to determine the fuzzy subsets. The input and output fuzzy sets are both defined as {negative large (NB), negative medium (NM), negative small (NS), zero (ZO), positive small (PS), positive medium (PM), positive large (PB)}. The error e and its rate of change ec are mapped into [-3, 3] for their fuzzy domain, while the tuning parameters Kp, Ki, and Ka are mapped into [-2, 2]. Based on the dynamic characteristics of the controlled object and relevant experience in adjusting the PID parameters, the speed deviateon e and its rate of change ec can be regarded as the input parameters of the fuzzy PID controller then self-tuning and adjusting. The parameters of the fuzzy PID control system are adjusted as follows.

$$K_p = k_p + \Delta K_P \tag{1}$$

$$K_I = k_I + \Delta K_I \tag{2}$$

$$K_D = k_D + \Delta K_D \tag{3}$$

where k_p, k_i, and k_d are the initial values of the controller, and Δk_p, Δk_i, and Δk_d are the self-tuning values of the controller. The final output value is represented by k, ki, and ka.

Then, the fuzzy rules ΔK_p, ΔK_i and ΔK_d are formulated as shown in Table 3.

Table 3: Fuzzy rule table for ΔKp, ΔKi, and ΔKd.

e	e_c						
	NB	NM	NS	ZO	PS	PW	PB
NB	PB NB PS	PB NB NS	PM NM NB	PM NM NB	PS NS NB	ZO ZO NM	ZO ZO PS
NM	PB NB PS	PB NB ZO	PM NM NB	PS NS NB	PS NS NB	ZO ZO NM	ZO ZO PS
NS	PM NB ZO	PM NM NS	PM NS NS	PM NS NM	ZO ZO NS	NS PS NS	NS PS ZO
ZO	PM NB ZO	PM NM NS	PM NS PM	ZO ZO NS	PS PS NS	NM PM NS	NM PM ZO
PS	PS NM ZO	PS NS ZO	ZO ZO ZO	NS PS ZO	NS PS ZO	NM PM ZO	NM PB ZO
PM	PS NM PB	ZO ZO NS	NS PS PS	NM PS PS	NM PM PS	NM PB PS	NB PB PB
PB	ZO ZO PB	ZO ZO PM	NM PS PM	NM PM PM	NM PM PS	NB PB PS	NB PB NB

Finally, we apply the deblurring according to formula 4:

$$y_0 = \frac{\sum_{i=1}^{n} y_i u(y_i)}{\sum_{i=1}^{n} u(y_i)} \tag{4}$$

where yi represents the discrete domain point, u (yi) represents the membership function value, and n is the number of single-point sets [19].

The fuzzy PID controller for this system, as shown in Figure 4 (c), is formulated by the above steps.

The exoskeleton has been designed and modeled in the previous section, and the comparison experiment between PID and fuzzy PID controllers is also designed. In this section, based on MATLAB, we will compare and verify the step tracking control effect of the two controllers.

The biomechanical data resource index website of the International Society of Biomechanics includes biomechanical data such as movement data, pressure data and muscle skeletal model data. In order to obtain control curves for gait tracking, we referenced human movement data from this website and imported it into MATLAB. At this time, all imported data is discrete points, which are not convenient for simulation control input. A cycle was selected and fitted using Fourier series expansion, with the following specific expression:

$$\theta_{gen}(t) = \sum_{n=1}^{N} a_n \sin(b_n t + c_n) \tag{5}$$

The fitted gait curve data is imported into the workspace for gait tracking control input. The lower limb rehabilitation exoskeleton robot and humanoid model are set up with joint connections and exported as URDF files, which can be directly imported into the MATLAB workspace. By calling this file through the program, the automatic calculation of the connection relationship between models can be avoided,

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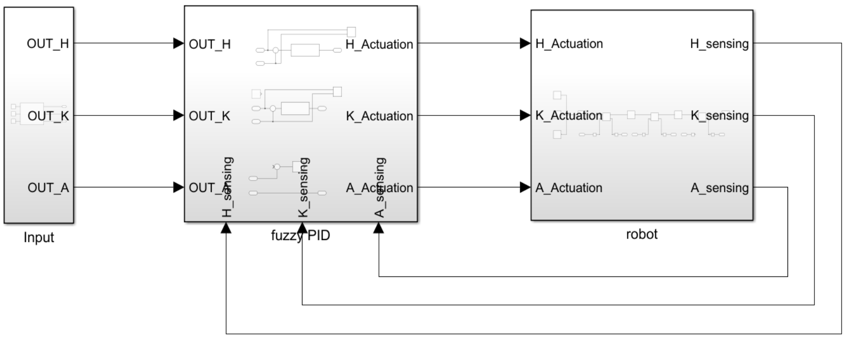
and the model construction can be carried out using the Simscape toolbox to avoid complex dynamic formula derivation and joint configuration, making the physical model simulation more rapid.

Add ground and contact, configure each joint as an external input for control and joint motion angle as output. At the same time, configure parameters such as damping coefficient and friction coefficient of joint motor. Since the size of exoskeletons and controller parameters can be changed, this experiment configures the quality and distribution of dummy model according to the mass and center of gravity mean value of different body segments of adult men in "Adult Human Inertia Parameters" (GB / T 17245-2004)[20], where the mass of each segment is shown in Table 4.

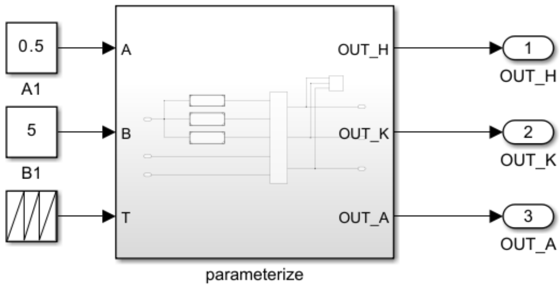
Table 4: The mass of each segment of the mannequin

Segment Name	**Head and Neck**	**Upper Torso**	**Lower Torso**	**Thigh**	**Shin**	**Foot**	**Upper Arm**	**Forearm**	**Hand**
Mass (kg)	5.16	10.07	16.30	8.50	2.20	0.89	1.46	0.75	0.38

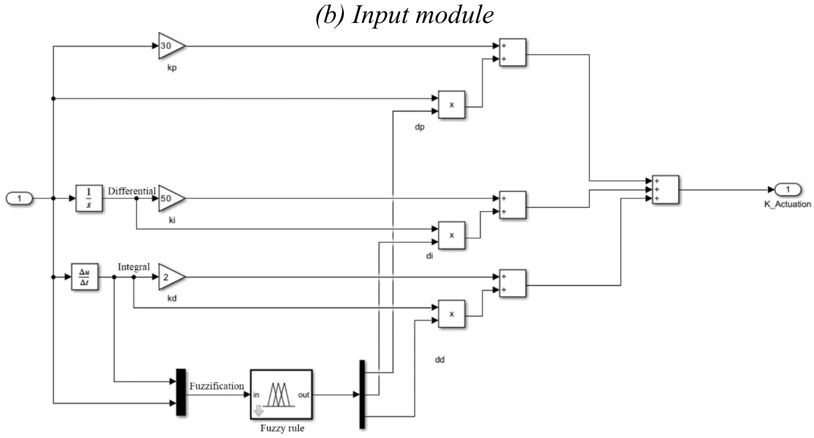
The lower limb rehabilitation exoskeleton robot simulation system is built by connecting the encapsulated input module and controller module, as shown in Figure 4.



(a) Overall model diagram



(b) Input module



(c) Controller module

(d) Simulation humanoid model

Figure 4: Simulink simulation model

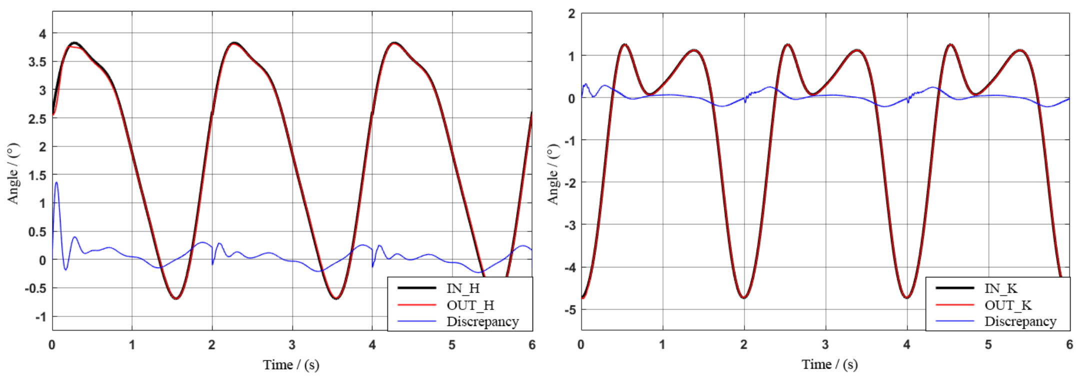
The output is the gait curve output module, and the plant is the PID/fuzzy PID controller. The gait curve is output through the function call module in the output, which can adjust the step length and stride of the gait curve by adjusting the adjustable parameters. The joint angle input from the exoskeleton model output and the gait curve input are processed as error inputs to the controller in the plant module, so that the driving torque of the joint can be obtained. Since the overall simulation system has multiple inputs and outputs, nonlinearity and uncertainty are large. In this experiment, the Simulink system APPS's System Control Designer was used for fast tuning of the PID parameters. System Control Designer is based on the principle of step response, and it can directly observe the step response curve of the system by dynamically dragging poles with intuitive Bode diagram, thus more efficiently obtaining better PID parameters. At the same time, fuzzy PID parameters were tuned using trial and error method, and the tuned parameters are shown in Table 5. The ankle joint is designed as a passive degree of freedom, so torque control is not considered for the controller.

Table 5: Control parameters for ΔK_P, ΔK_i, and ΔK_d.

Joints	Traditional PID	Fuzzy PID
Hip	50.5, 30.3, 1	60, 15, 2
Knee	60.2, 15.5, 1	60, 30, 2

3.2 Analysis of the Simulation Results for Gait Tracking

After completing the simulation, comparisons will be made between the reference gait curve as shown in Figure 5 and Figure 6, tracking trajectory curve and error curve as shown in Figure 7.



(a) Hip joint *(b) Knee joint*

Figure 5: Traditional PID Gait Tracking Curves

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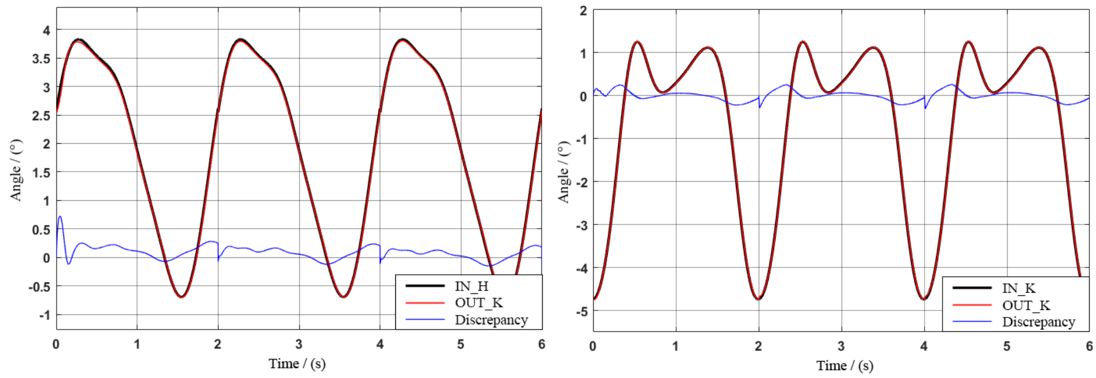
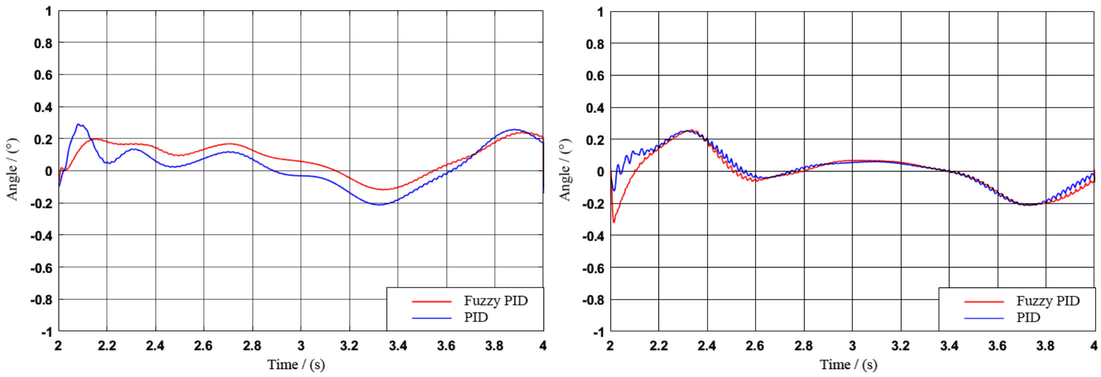


(a) Hip joint *(b) Knee joint*

Figure 6: The fuzzy PID gait tracking curve



(a) Hip joint *(b) Knee joint*

Figure 7: Local error comparison of gait tracking

The hip joint tracking curve is shown in Figure 5 (a). Within the first cycle t = 0 ~ 2 s, the error only stabilizes at t = 0.3 s, and the maximum overshoot reaches 1.1 °. Although the knee joint can better fit the reference curve, there are obvious sawtooth-shaped error curves at the corners of t = 2 s and 4 s. This is because the gait curve changes abruptly, the response of the PID controller is fast, but the stabilization time is long, resulting in a sawtooth fluctuation of errors.

Based on the hip and knee gait curves in Figure 6, which are controlled by a fuzzy PID controller, the error of the hip joint tends to stabilize at t = 0.2 s during the first cycle. Compared with traditional PID control, its error curve is smoother at the corner, and it can continuously approach the reference gait curve while maintaining stability.

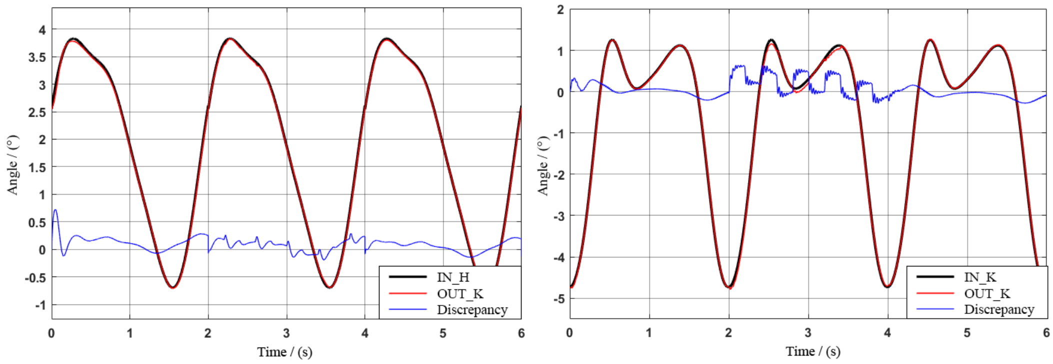
The hip joint trajectory tracking curves of the two controllers, as shown in Figure 7, both exhibit error fluctuations at t = 2 s and 4 s, mainly affected by the large knee joint corner at t = 2 s and 4 s. Based on the above analysis of the joint trajectory tracking curve, it can be concluded that although the PID response is fast, its stability is poor and prone to fluctuation. The fuzzy PID has a relatively slow response but short stabilization time, smaller maximum overshoot, and smoother error curve.

3.3 Analysis of Simulation Results for Spasms

To simulate the real situation of patients walking, it is usually simulated by adding external interference signals or step signals at the joint to reflect the robustness of the controller. However, due to spasticity in the lower limbs, patients are affected by both themselves and the environment, making walking more difficult[21]. Therefore, the anti-interference analysis for lower limb rehabilitation exoskeleton robots should be experimentally simulated through simulation experiments simulating sudden spastic symptoms during rehabilitation training.

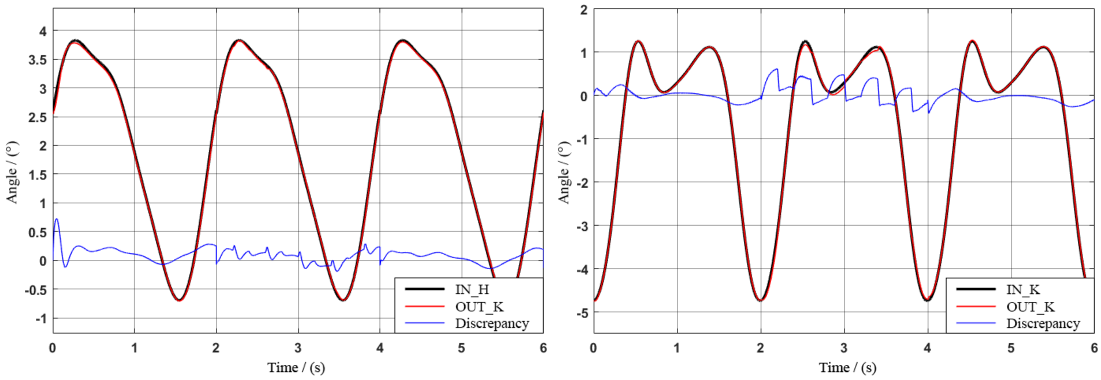
A torque of magnitude 30 Nm, with a period of 0.4 s and an opposite direction to the walking direction was applied to the knee joint in the simulation experiment to simulate sudden spasticity during actual walking. The experiment started at t = 2.0 s and lasted for 2 s. After introducing this disturbance into the system, the simulation curves of hip and knee joint gait tracking controlled by traditional PID and fuzzy

PID controllers are shown in Figure 8 and Figure 9 respectively. And Figure 10 shows the local error amplification comparison.



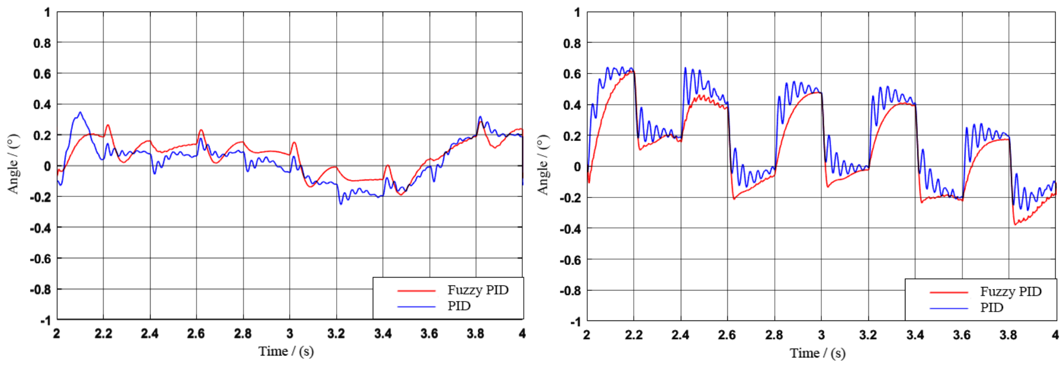
(a) Hip joint *(b) Knee joint*

Figure 8: The traditional PID gait tracking curves in spasticity case



(a) Hip joint *(b) Knee joint*

Figure 9: Fuzzy PID gait tracking curves in the case of spasticity



(a) Hip joint *(b) Knee joint*

Figure 10: Local error comparison for the case of spasm

When simulating spasms, both controllers still maintain good tracking of the hip joint and have a small overshoot in the gait tracking curve. The main comparison of knee joint control shows that fuzzy PID has stronger anti-interference ability. Under the influence of sudden spasm, the maximum overshoot of PID controller is 0.7 degrees, and there are fluctuations of up to 0.1 degrees on the error curve as shown in Figure 10, indicating that although the response is relatively fast when disturbed, it makes it difficult to stabilize, forming a sawtooth-shaped error curve with poor control effect; Fuzzy PID controller has a maximum overshoot of 0.6 degrees and a smoother tracking trajectory curve during spasm. This indicates that when lower limb exoskeletons undergo rehabilitation training and are interfered by sudden spasm, PID controller has low stability and cannot well protect patient's joints. However, fuzzy PID has better self-adaptability after disturbance, can better protect patients' joints, and has stronger anti-interference ability.

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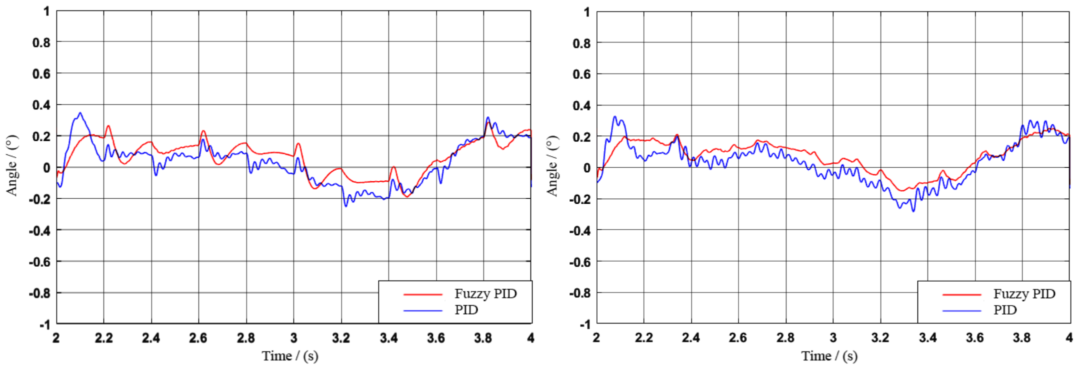
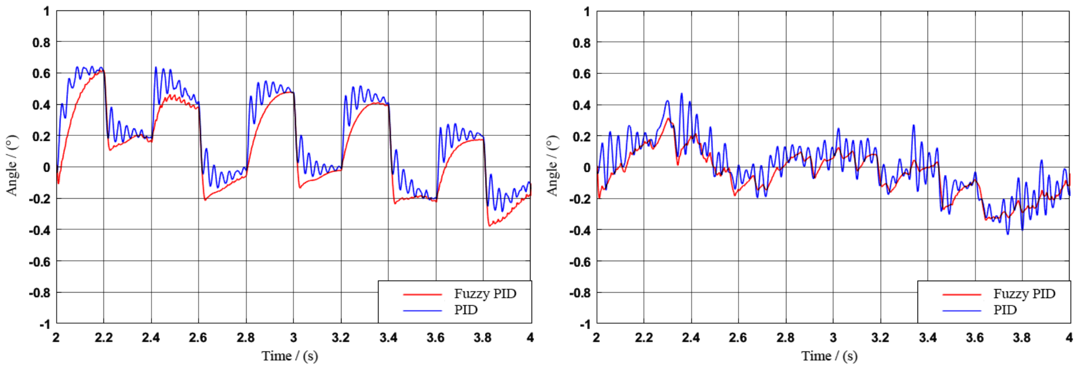
3.4 Noise Interference Assessment Comparison

Introduce a 2 s noise interference signal at t = 2 s, and compare the experimental results with the error curve in spasticity as shown in Figure 11 below.



(a) Spasticity interference of hip joint *(b) noise interference of hip joint*



(c) Spasticity interference of knee joint *(d) noise interference of hip joint*

Figure 11: Local error comparison in two evaluation methods

As shown in Figure 11 (a), (b), there is no significant difference between the two evaluation methods for hip joint, mainly comparing knee joint error results. As shown in Figure 11 (c), (d), both PID and fuzzy PID have faster response speed and larger overshoot in the two evaluation methods. However, only fuzzy PID shows obvious lagging and adaptability under spasticity evaluation method. Under continuous spasticity interference, the response of fuzzy PID lags and changes smoothly without local fluctuations, while the overall overshoot range decreases from 0.6° to below 0.2°. Its lagging and adaptability can well adapt to the patient's spastic symptoms and protect the patient's joints. In the noise interference evaluation method, it cannot effectively stimulate the adaptive ability of fuzzy PID.

4. Conclusion

This paper designs a lower limb rehabilitation exoskeleton robot for stroke patients, and the model is imported into Matlab/Simulink to establish a simulation model. Traditional PID/fuzzy PID controllers are used for simulation experiments, and the performance of the controller under two different evaluation methods is compared and analyzed. The specific conclusions are as follows:

(1) A lower-limb exoskeleton robot structure for rehabilitation training is designed, with a single leg using 5 degrees of freedom and non-coaxial joint design. It provides reference for the research and design of lower-limb rehabilitation exoskeleton robots.

(2) Simulink and URDF are used to build a lower limb exoskeleton model. The walking curve is inputted for simulation experiment, and the parameters of two kinds of PID controllers are dynamically tuned with System Control Designer, which not only has high efficiency but also the exported parameters have good adaptability.

(3) Using the torque data of human spasticity to replace noise signals for interference performance evaluation and analysis. Comparing the results of the two evaluation methods, it was found that the evaluation method of spasticity can effectively stimulate the anti-interference performance of fuzzy PID.

Compared with the evaluation method of noise interference, this method can more accurately evaluate its protective effect on patients and reflect the controller's performance in actual situations, providing strong support for the selection and optimization design of lower limb rehabilitation exoskeleton controllers.

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