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The Response Speed Performance of Lower Limb Rehabilitation Robots based on Different PID Algorithms

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Abstract:
Nowadays, the aging of the population is common in the world, and the increase in age makes the incidence of stroke rise sharply. The Stroke can directly affect human movement ability, once suffering from it, it will seriously affect people's quality of life. As an important new type of medical equipment, the traditional PID control algorithm of the lower limb rehabilitation robot has limitations in response field, such as response speed and overshoot. However, there are gaps in the research on the response speed of different new PID algorithms. The purpose of this paper is to introduce the traditional PID algorithm and some new PID algorithms through literature retrieval, and evaluate the performance of the algorithm by comparing the response curves of different algorithms. It is found that the fuzzy PID algorithm and the improved GWO-PID algorithm perform better than the traditional algorithm in terms of response speed. This paper compares the response performance of different PID algorithms, which can not only help researchers understand the principle of the corresponding algorithm, but also help researchers compare the response performance between different algorithms.

Keywords: Lower limb rehabilitation robot; PID control algorithm; PID algorithm improvement; Response performance

1. Introduction

According to the United Nations' 2022 World Population outlook data and China's seventh national census data, the world's population aging phenomenon is on the rise, and population aging has become a social problem that must be faced by global development [1]. With the growth of age, the elderly will inevitably be more prone to disease [2]. The incidence of stroke will rise sharply. This disease will seriously affect people's exercise ability, and the disease of walking will seriously affect the quality of life of patients. Therefore, it is very important to restore walking ability, which helps to reduce complications and restore motor work ability [3]. The lower limb Medical Rehabilitation Exoskeleton Robot is a medical device that assists patients in rehabilitation training and improves the motor function of lower limbs by integrating the mechanical structure and the intelligent electronic control system [4], helping patients automate repetitive and intensive training in the rehabilitation process [5].

As a new medical device, the lower limb rehabilitation robot can effectively help patients recover their motor function, but the existing robots also have some problems [6]. Good human-computer interaction can promote the development of rehabilitation robots, but the safety and comfort of the existing control system still need to be improved [7]. Because patients with lower limb diseases cannot control their actions autonomously, an appropriate control algorithm and response speed can effectively improve the safety and experience of the robot. The classical PID control algorithm is widely used in mechanical control systems due to its low complexity and relatively stable characteristics [8]. However, due to the strong time-varying and nonlinear factors in the process of lower limb rehabilitation, the traditional PID algorithm can not complete rapid response and accurate control. However, patients may need to quickly adjust their posture due to sudden situations such as muscle spasms during rehabilitation training. If the response speed is slow, the robot will not be able to match the human action in real time. Although the rehabilitation robot technology has shown great potential in the medical field, it still needs continuous innovation to improve its treatment ability [9]. Therefore, different new PID algorithms are continuously developed and put into use.

This paper aims to introduce and analyze the existing lower limb robots based on different PID control logic, compare them and summarize their respective characteristics, show the response speed of different control systems, and provide readers with an algorithm response performance comparison. On this basis, this study considers how to improve the existing algorithms and predict the future development trend.

2. Algorithm Framework and Basic Principles

2.1 Classic PID Algorithm

The PID control system is composed of three parts, namely, proportion, integral and differential. The PID control algorithm uses the linear combination of proportion, integral and differential to control by calculating the system error in real time. The classical PID algorithm is often used in the control system of the lower limb rehabilitation robot. The overall structure is shown in Figure 1 below.

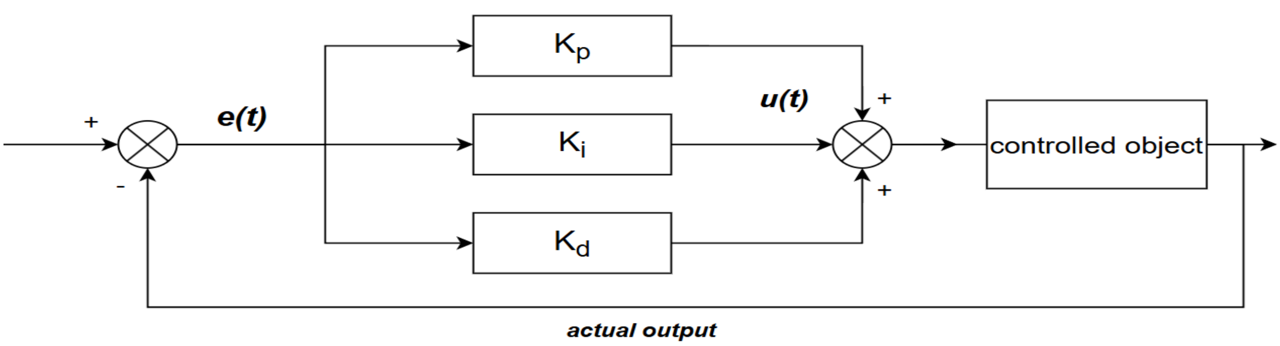

Fig. 1 Block diagram of PID control system [10]

The linear combination relationship between input and output and proportion, integral and differential in the PID system block diagram is as follows.

$$u(t) = K_P e(t) + K_I \int_0^t e(t)dt + K_D \frac{de(t)}{dt} \tag{1}$$

K_P is the proportional adjustment coefficient, K_I is the integral adjustment coefficient, and K_D is the differential adjustment coefficient. These parameters correspond to the three control modes of the PID control algorithm, and e(T) represents the function of the difference between the current value and the target value of the system over time. The $K_P e(t)$ part is proportional control, which adjusts the output value by ensuring that the corrected output of the system is proportional to the difference at the current time, and uses K_P for adjustment. The larger the system difference is, the more supplementary the proportional control provides, and the greater the corresponding control force. The $K_I \int_0^t e(t)dt$ is an integral control, which adjusts the output value by ensuring that the final output of the system is in positive proportion to the difference accumulated over time, and uses K_I to adjust. As long as the difference exists, the integral control will control by accumulating the difference several times to eliminate the steady-state error that cannot be eliminated by the proportional control.

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The $K_D \frac{de(t)}{dt}$ part is differential control, which adjusts the output value by ensuring that the final output of the system is proportional to the change rate of the difference, and uses K_D to adjust. The differential control algorithm does not pay attention to the difference of the system, but predicts the direction and controls in advance through the change speed and direction of the difference to prevent the system from exceeding the set value.

Jinhao team from Chongqing University of Technology developed a lower limb gait rehabilitation training robot. The PID control method was used as the passive control method of the system, and the effectiveness of passive training was verified by comparing the planned trajectory with the actual trajectory. According to the trajectory analysis of ankle and knee joints, it is successfully confirmed that the algorithm can meet the operation requirements [11].

2.2 Fuzzy PID Algorithm

Fuzzy theory transforms human thinking into specific fuzzy rules and identifies them by computer. It is usually used in the control of the complex application environment [10]. While retaining the basic framework of the original PID algorithm, the fuzzy PID algorithm combines the fuzzy theory with it, and uses the fuzzy controller to establish a parameter self-adjusting mechanism to adjust the three PID parameters in real time. Its overall framework is shown in Figure 2 below.

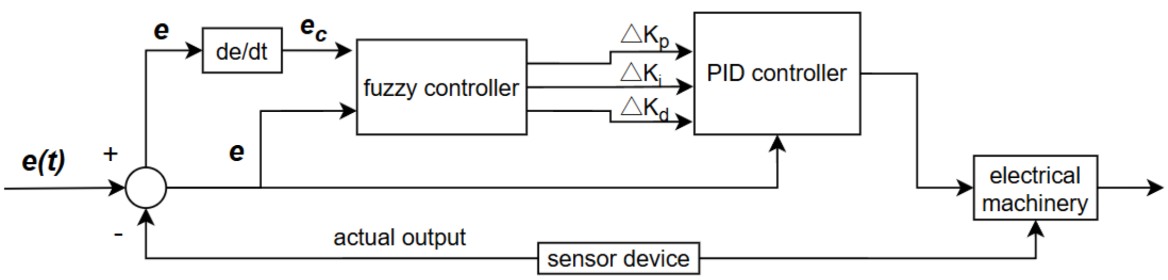

Fig. 2 Block diagram of Fuzzy-PID control system [10]

The fuzzy PID algorithm takes the difference between the current value of the system and the specified value and the change rate of the difference as input variables, and takes $\Delta K_P, \Delta K_I, \Delta K_D$ as output data to adjust PID parameters.

$$\begin{cases} K_P(t) = K_P(0) + \Delta K_P(t) \\ K_I(t) = K_I(0) + \Delta K_I(t) \\ K_D(t) = K_D(t) + \Delta K_D(t) \end{cases} \tag{2}$$

The algorithm first converts the input difference value and the change rate of the difference value into fuzzy language variables through the membership function preset by the system. Membership function is a mathematical function that converts the accurate value into a fuzzy set grade. Due to different subjective cognition, there is no unified standard for membership function at present. Its general forms are triangular membership and Gaussian membership [10]. There are many expression modes of membership of fuzzy sets, which are usually divided by grades such as “NB”, “PM”. The core of a fuzzy controller is fuzzy control rules [12]. Fuzzy control rules can calculate the fuzzy set membership of output variables according to the fuzzy set membership grade of input variables, which are mostly developed by researchers’ experience or test data analysis [10].

After fuzzifying the input data and processing the fuzzy rule base. The system needs to clear the fuzzy quantity into the available accurate quantity to complete the subsequent control. This requires the system to infer the relationship between the fuzzy set and the data set, which is usually converted using the maximum membership method, the center of gravity method and the area bisection method [10]. The system will use the final data to adjust the parameters.

Zhangwenrui team from North China University of Technology used the fuzzy PID algorithm in the design of the wearable lower limb exoskeleton rehabilitation robot, designed a fuzzy controller for the lower limb rehabilitation robot for real-time control of single joint trajectory, and obtained the corresponding test curve in the MATLAB environment [13].

2.3 GWO-PID Algorithm

In 2014, Australian scholar Mirjalili and others proposed a new algorithm, the gray wolf optimization algorithm (GWO), based on the efficient way of gray wolf cooperative hunting [14]. In the improved GWO-PID algorithm, you are a hunter. The improved GWO algorithm is equivalent to an efficient wolf pack. It helps you find the best parameters through cooperation, that is, the three PID parameters corresponding to the first wolf to capture the optimal response of the system. Jiangjinjin team from Chongqing University of Technology used the improved GWO-PID algorithm control algorithm in the pedal lower limb rehabilitation robot. It was tested in the cosimulation environment of Adams and MATLAB, and the excellent crank speed response curve was obtained. The specific framework is shown in the Fig 3 [15].

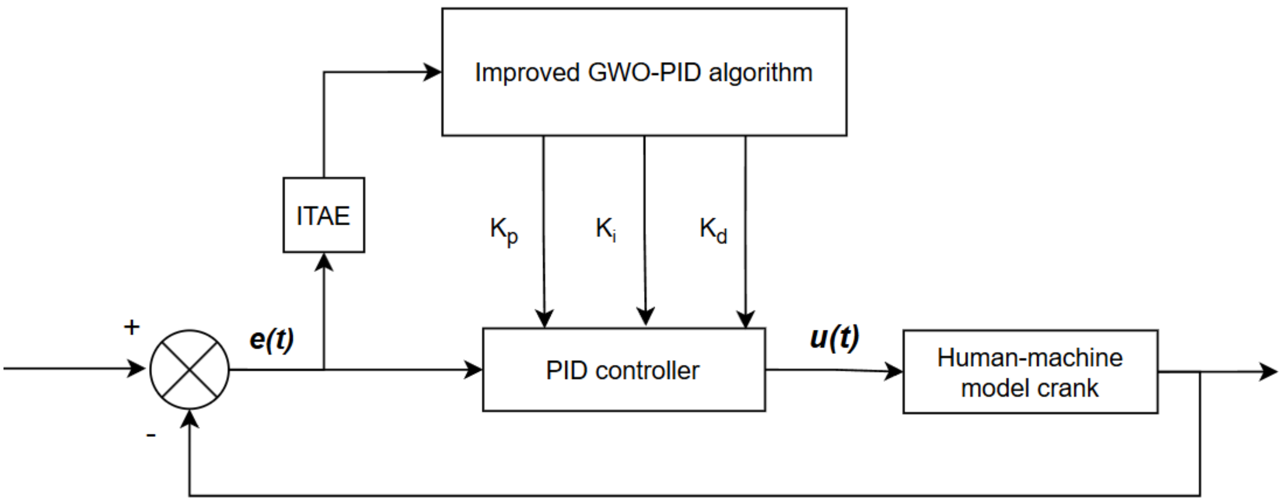

Fig. 3 Block diagram of Improved GWO-PID control system [15]

2.3.1 The Principle of Grey Wolf Optimization Algorithm

Gray wolf society follows a strict hierarchy, as shown in the figure. The wolf alpha, the leader of the highest level, has absolute leadership and dominates the hunting operation. The deputy leader wolf beta assists the alpha in managing the colony. As the middle layer, wolf δ obey α and β, and provides assistance in hunting. The bottom ω wolf with the largest number executes all superior instructions unconditionally. Fig 4 shows the ranking of wolf packs.

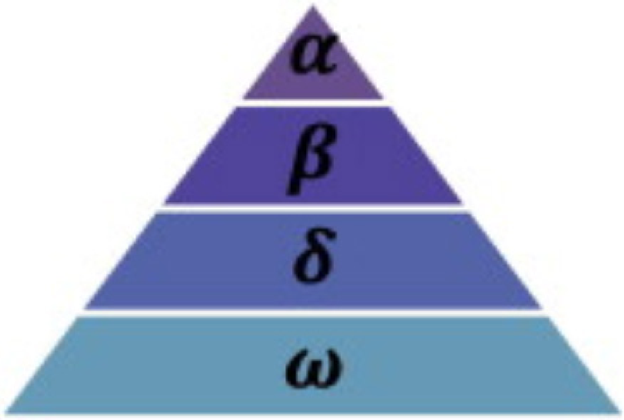

Fig. 4 Ranking of wolf packs [14]

The hunting process of the gray wolf group is roughly as follows. When wolf α was the first to find the trace of prey, wolf β and wolf δ, who are in a lower position, immediately cooperated to command the wolves to carry out hunting. The wolf ω adjusts its position according to the position of the high and low wolves, and shrinks the encirclement synchronously from different directions according to the leader's instructions, gradually approaching the target to complete the hunt.

The grey wolf optimization algorithm establishes the model when the grey wolf surrounds the prey [15]

$$D = \left| C \bullet X_P(t) - X(t) \right| \tag{3}$$

$$X(t+1) = X_P(t) - A \bullet D \tag{4}$$

D represents the distance between the gray wolf and its prey, X represents the direction in which the gray wolf constantly updates, and the parameters a and C are system vectors. Its mathematical formula is as follows:

$$A = 2a \bullet r_1 - a \tag{5}$$

$$C = 2r_2 \tag{6}$$

The parameters R1 and R2 are random variables within the [0,1] interval, which affect a and C respectively, ensuring the randomness of the algorithm. Parameter a represents the exploration ability of wolves, and its range is [-2,2]. As the convergence factor a decreases from 2 to 0, the value of a also changes correspondingly. When the absolute value of a is greater than 1, the imitation wolf pack expands its range due to the absence of prey. When the absolute value of a gradually shrinks to less than 1, the wolves stop searching for new areas and surround the location of the current optimal solution. Parameter C is always random and used to simulate the uncertainty in the

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natural environment [14]. The grey wolf optimization algorithm adjusts the position of each wolf (PID parameter) through the wolf hierarchy, and finally captures prey (PID optimal parameter). Firstly, a group of “gray wolves” representing different solutions is initialized by the algorithm, and each wolf corresponds to a set of PID parameters. The fitness of each wolf is calculated in different ways, such as the ITAE index of absolute value time integration function, and the formula is as follows.

$$ITAE = \int_0^\infty t\left|e(t)\right|dt \tag{7}$$

By ranking the fitness, the social level can be determined. The lower the fitness is, the closer the solution is to the optimal solution. The three leading wolves α, β and δ, represent the optimal, suboptimal and third optimal solutions respectively. Other wolves update their positions according to the positions of the three leading wolves. Use the formula above to locate the position of the three leading wolves to find the prey position, and then gradually guide other wolves to move in the right direction.

$$\begin{cases} D_\alpha = \left|C_\alpha \bullet X_\alpha(t) - X(t)\right| \\ D_\beta = \left|C_\beta \bullet X_\beta(t) - X(t)\right| \\ D_\delta = \left|C_\delta \bullet X_\delta(t) - X(t)\right| \end{cases} \tag{8}$$

$$\begin{cases} X_\alpha = X_\alpha(t) - A_\alpha \bullet D_\alpha \\ X_\beta = X_\beta(t) - A_\beta \bullet D_\beta \\ X_\delta = X_\delta(t) - A_\delta \bullet D_\delta \end{cases} \tag{9}$$

$$X(t+1) = \frac{X_\alpha + X_\beta + X_\delta}{3} \tag{10}$$

2.3.2 Improved GWO-PID Algorithm

The improved algorithm is optimized in three aspects.

Because the uncertainty of randomly initializing wolves is too strong, it may lead to the location aggregation of each gray wolf and affect the overall effect. Thanks to its good non-repetition, chaotic sequences can be used to optimize the initialization logic [16], whose function is expressed as

$$X_{n+1} = sin\left(\frac{a\pi}{X_n}\right) \tag{11}$$

Due to the uncertainty of the real environment, most of the convergence factors are nonlinear decreasing. Linear decreasing will affect the value of a in the algorithm and change the search ability. The improved algorithm uses the following functions to balance, where λ is a random variable greater than or equal to 0, and t is the number of iterations [17].

$$a = a_{min} + \frac{a_{max} - a_{min}}{\lambda} \times gamma\left(\lambda, 1 - \frac{t}{t_{max}}\right) \tag{12}$$

In the normal algorithm, when the positions of the three leading wolves are used to guide the movement of other wolves, the guiding power of the three leading wolves is the same, which will lead to slow convergence [18]. This problem can be well solved by introducing dynamic weights. The specific formula is as follows.

$$X(t+1) = \frac{(\mu_1 X_1 + \mu_2 X_2 + \mu_3 X_3)}{3} \tag{13}$$

The weight index is obtained by the following formula.

$$\begin{cases} \mu_1 = \dfrac{|X_1|}{|X_1| + |X_2| + |X_3|} \\ \mu_2 = \dfrac{|X_2|}{|X_1| + |X_2| + |X_3|} \\ \mu_3 = \dfrac{|X_3|}{|X_1| + |X_2| + |X_3|} \end{cases} \tag{14}$$

3. Discussion

3.1 Algorithm Similarities and Differences

The classical PID algorithm is the basis of two new algorithms, but its PID parameters are not adjustable. The fuzzy PID algorithm is based on the classical PID algorithm and integrates the fuzzy theory. Through the fuzzy control output adjustment value, the PID parameters are no longer fixed, but can be adjusted automatically. The improved GWO-PID algorithm is the same as the fuzzy PID algorithm in parameter adjustment, which is adjusted by the adjustment value output by the algorithm. The difference is that the improved GWO-PID algorithm combines the improved gray wolf optimization algorithm with the classic PID, and outputs the adjustment according to the improved gray wolf optimization algorithm. These two algorithms are based on the classical PID algorithm and integrated with other algorithms, so that the parameters of PID can be adjusted automatically. Compared with the classical PID algorithm, they enhance the adaptability to a complex environment. By comparing the response test data of three different algorithms in the lower limb rehabilitation robot, the study can further evaluate their performance. The performance of the two new algorithms is better than that of the classical PID algorithm in terms of overshoot and corresponding speed. The following is the specific performance evaluation.

3.2 Algorithm Performance Evaluation

The crank speed is the key index of the control system of the lower limb rehabilitation robot, and its response curve directly reflects the performance of the robot's control system. Jiangjinjin's team from Chongqing University of Technology designed a pedal-type lower limb rehabilitation robot, and tried to use a fuzzy PID algorithm and an improved GWO-PID algorithm respectively. The fuzzy PID algorithm is simulated in the Simulink environment, and the response curve is obtained by inputting the crank speed of 60 °/s. In the response diagram of the left normal signal, the fuzzy PID overshoot is basically zero. The maximum overshoot of the classical PID algorithm is 13%, and the steady-state time is 0.6 seconds, which is longer than that of the fuzzy PID algorithm [19]. In the response diagram of the right sinusoidal signal, it can be clearly found that the error of the classical PID algorithm is large between 0 and 0.4 seconds, and the steady-state time is longer than that of the fuzzy PID algorithm. According to the two kinds of response images, it can be determined that the performance of the fuzzy PID algorithm in the crank speed response test is better than that of the classical PID algorithm.

Another improved GWO-PID algorithm is co-simulated by Adams and MATLAB. The response curve was obtained by inputting the crank speed of 60 °/s. The response steady-state time of the improved GWO-PID algorithm is about 0.3s, and the speed is 78% and 54% higher than that of the traditional PID control algorithm and GWO-PID control algorithm respectively [15]. At the same time, it can also be found that the initial delay time of the GWO-PID algorithm is the shortest among the three algorithms through the enlarged image of 0 to 0.3 seconds. The response performance of the improved GWO-PID algorithm is better than that of the classical PID algorithm in both steady-state time and delay time.

Wang Jie team from Guangxi University of science and technology used fuzzy PID algorithm and Mamdani reasoning method to load the fuzzy rules of the team in the design of the dynamic balance weight reduction system of the running table type lower limb exoskeleton rehabilitation robot, completed the simulation of the robot, and obtained the weight reduction response simulation results in the Simulink environment. The fuzzy PID controller can be stable in about 5S, while the PID controller needs about 7S [20]. At the same time, the overshoot and tracking error of the fuzzy PID algorithm and the classical PID algorithm are compared. The overshoot of the traditional PID algorithm is larger, and the tracking accuracy is lower than that of the fuzzy PID algorithm. The tracking accuracy and response speed of the fuzzy PID algorithm are better than those of classical PID [20].

Unit step signal refers to the signal that jumps from 0 to 1 when time t=0, and remains 1 when t>0. Because of the characteristics of signal mutation, it is widely used to evaluate the performance of a control system. Zhangwenrui's team from the North China University of Technology used a fuzzy PID algorithm in the design of a wearable lower limb exoskeleton rehabilitation robot. By setting various parameters and loading fuzzy control rules, the simulation of the robot algorithm was completed, and the unit step signal simulation results in the MATLAB environment were obtained. Through comparison, it is found that the fuzzy PID algorithm not only has a significantly faster initial rising speed than the classical PID algorithm, but also has a lower overshoot than the classical PID algorithm, and the time to reach the stable state is also significantly less than the classical PID algorithm [12]. It can be proved that the response control effect is better than the classical PID algorithm.

3.3 Algorithm Limitations and Future Trends

Through the research, it can be found that the fuzzy PID algorithm combines the classical PID algorithm and fuzzy theory to describe the system more accurately, and adjusts the PID parameters through the fuzzy control module, so as to achieve the purpose of self-regulation. The improved GWO-PID algorithm is to learn from the experience of the gray wolf species hunting, integrate the improved gray wolf optimization algorithm and PID algorithm, and converge the parameters to the optimal solution by simulating the hunting process. However, although the two new algorithms are better than the classical PID, they also have their own limitations that need to be improved. For example, the current membership function of the fuzzy PID algorithm depends on the experience of engineers and is mixed with some subjective factors. In future research, we should try to use quantitative methods to avoid relying too much on experience and determine specific quantitative indicators to evaluate its availability. The improved GWO-PID algorithm needs to consider how to further enhance the ability to find the optimal solution while reducing the time to find the optimal solution, so as to avoid falling into local optimization and taking a long time.

The classical PID algorithm has a long development time and is the most commonly used control algorithm. However, due to its fixed parameters, it is difficult to apply to a complex medical environment. Based on the current research to speculate on the development trend of the PID algorithm. The new PID algorithm in the field of lower limb rehabilitation robots in the future may be developed around parameter adaptive adjustment. By combining

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the framework of the classical PID algorithm with other theories, this paper attempts to establish a set of PID algorithms that can automatically adjust parameters by using different algorithm logic, so as to strengthen the adaptability of the algorithm in a complex medical environment, and then continuously optimize the human-computer interaction experience of the lower limb rehabilitation robot.
Conclusion
Through the investigation of the existing literature, this paper found that the classical PID algorithm cannot automatically adjust the parameters, which will lead to a reduction of the adaptability of the algorithm in the complex medical environment. Therefore, many algorithms are optimized on the basis of the classical PID algorithm. The response speed of the lower limb rehabilitation robot using different PID algorithms is different. This paper introduces the principle of the classical PID algorithm and two new PID algorithms, and analyzes the test structure based on the algorithm. By analyzing the response curves of lower limb rehabilitation robots designed by different teams, the similarities and differences of different algorithms and the advantages and disadvantages of performance are obtained. From the existing results, the performance of the two new PID algorithms in the response field is better than the traditional PID algorithm. It not only reduces the time required for the system to reach the steady state, but also reduces the overshoot caused by the algorithm, which effectively improves the shortcomings of the classical PID algorithm. This paper makes up for some gaps in the summary of the response speed of different PID algorithms, which is conducive to the understanding of different algorithm logics by researchers in the field of control systems and the comparison between algorithms by researchers. At the same time, according to the existing situation, the paper speculates on the future development trend, that is, the integration of other theories on the basis of PID. However, the current research still has limitations. There are many ways to improve the PID algorithm. This paper only focuses on the fuzzy PID and improved GWO-PID algorithms. Future research can gradually expand the scope and include more algorithms in the research.

4. Conclusion

Through the investigation of the existing literature, this paper found that the classical PID algorithm cannot automatically adjust the parameters, which will lead to a reduction of the adaptability of the algorithm in the complex medical environment. Therefore, many algorithms are optimized on the basis of the classical PID algorithm. The response speed of the lower limb rehabilitation robot using different PID algorithms is different. This paper introduces the principle of the classical PID algorithm and two new PID algorithms, and analyzes the test structure based on the algorithm. By analyzing the response curves of lower limb rehabilitation robots designed by different teams, the similarities and differences of different algorithms and the advantages and disadvantages of performance are obtained. From the existing results, the performance of the two new PID algorithms in the response field is better than the traditional PID algorithm. It not only reduces the time required for the system to reach the steady state, but also reduces the overshoot caused by the algorithm, which effectively improves the shortcomings of the classical PID algorithm. This paper makes up for some gaps in the summary of the response speed of different PID algorithms, which is conducive to the understanding of different algorithm logics by researchers in the field of control systems and the comparison between algorithms by researchers. At the same time, according to the existing situation, the paper speculates on the future development trend, that is, the integration of other theories on the basis of PID. However, the current research still has limitations. There are many ways to improve the PID algorithm. This paper only focuses on the fuzzy PID and improved GWO-PID algorithms. Future research can gradually expand the scope and include more algorithms in the research

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