Research on fuzzy PID lower extremity exoskeleton control system based on pneumatic drive

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Abstract. The lower extremity rehabilitation exoskeleton based on pneumatic muscle actuator was introduced. The gait experiments were implemented, and the biomechanics of human walking were outputted for the design and control of lower rehabilitation exoskeleton. The experiment platform was built based on DSPACE system and the fuzzy adaptive PID controller was applied for the control of lower rehabilitation exoskeleton. The experiment results showed that adding the pre-feedback control based on fuzzy adaptive PID can significantly reduce the time that the system, and the experiment of swing control also showed that a high level of coordination between the user swing motion and the exoskeleton leg.

1. Introduction
The lower extremity exoskeleton system is a mechatronic device that provides walking assistance for the human body or rehabilitation training for disabled patients [1]. Since the beginning of the study of exoskeleton robots in the 1960s, many advances have been made in the study of exoskeleton robot systems. It involves subjects such as bionics, mechanics, sensing, and automatic control. There are many types of exoskeleton drivers, including motor, hydraulic and pneumatic. The advantages of motor are high control precision and fast response. Hydraulic drive has the characteristics of simple structure and stable operation. Pneumatic drive mainly uses pneumatic muscles with high power-to-mass ratio, Clean, non-polluting and flexible. Among them, aerodynamic muscle belongs to a new type of drive, which was first invented by Joseph L. Mckibben and later developed into a more perfect pneumatic muscle. At present, many scientific research institutions in China have begun to use pneumatic muscles as a drive for the study of lower extremity exoskeleton [2-3]. From the point of the driving method, some are driven by pneumatic muscles with springs, and some are driven by two pneumatic muscles on the mechanism rod. In this paper, two pneumatic muscles are used to connect the joints through the wire rope lasso. Because the structure of the pneumatic muscle is more complicated which are consisted of a thin-walled capsule, a woven mesh, a rubber layer and a metal sleeve at both ends. The output tension, its internal pressure and contraction length have coupling relationships which are difficult to build accurate mathematical models [4]. In this paper, the feedforward fuzzy PID control algorithm is not very dependent on the dynamic model of the control system, and it can achieve high control precision and meet the control precision requirements of the lower extremity exoskeleton.
2. Control Strategy Research

2.1 Acquisition of human gait

The motion analysis system is used to perform normal walking gait experiments. During the experiment, the human body needs to be marked as shown in Figure 1. When the human body is walking normally, the joint angle of the lower limbs is a cyclical change process. In a cycle, from the perspective of a single leg, the human walking process is divided into a swing phase and a support phase. The swing phase accounts for about 40% of the human body's walking, and the supporting phase accounts for 60%. Figure 2 and figure 3 reveals the gait information of the lower extremity joints when the human body walked. This signal is used as a desired signal for lower extremity exoskeleton control. The person performing the gait experiment has a height of 175 mm and a body weight of 65 kg. The range of hip and knee motion angles is shown in Table 1.

![Walking Experiment](image)

**Fig.1** walking experiment

![Hip Joint Angle](image)

**Fig.2** Hip joint angle of walking experiment

![Knee Joint Angle](image)

**Fig.3** Knee joint angle of walking experiment

And the red line represents the experimental value of the right leg, and the blue line represents left leg, the gray line represents the theoretical estimate of the system. From the Figure 2 and Figure 3, We can conclude Table 1.

| Movement form | Hip joint | Knee joint |
|---------------|-----------|------------|
| Flexion/extension $(\theta_1)$ | Outreach/receipt | External rotation / internal |
|                         | Flexion/extension $(\theta_2)$ | External rotation / internal |
Normal range of motion | rotation | rotation
--- | --- | ---
-10°~30° | -5°~3° | -7°~3° | 0°~67° | 8.6°~8.6°

2.2 Design of fuzzy PID controller

The fuzzy controller is composed of a fuzzifier, a fuzzy inference engine and a defuzzifier [5]. The fuzzy controller is designed by using the fuzzy toolbox (GUI) in MATLAB. Two input quantities are added to the toolbox, and the input quantity is the tracking error e and the error rate of change \( \dot{e} \). The output is the ratio of the PID parameters. The adjustments of the integral and differential are \( \Delta K_p \), \( \Delta K_i \) and \( \Delta K_d \). The domain of e and \( \dot{e} \) is set to (-6,6), and the fields of \( \Delta K_p \), \( \Delta K_i \) and \( \Delta K_d \) are set to (0,6), (0,3), (0,3), and fuzzy language variable settings. For NB (negative large), NM (negative medium), MS (negative small), ZO (zero), PS (positive small), PM (median), PB (positive), the membership function selects a triangle function (trimf) [6-7]. Deblurring uses the center of gravity method as shown in equation (1).

\[
z_0 = \frac{\sum_{i=0}^{n} \mu_{i} (z_i) \cdot z_i}{\sum_{i=0}^{n} \mu_{i} (z_i)}
\]  

(1)

\( z_0 \) is the exact value of the fuzzy controller output; \( z_i \) is the value in the fuzzy control quantity domain; \( \mu_{i} (z_i) \) is the membership value of \( z_i \). Figure 4 reveals the control block diagram of the fuzzy PID. The expression of the fuzzy PID controller is shown in equation (2).

\[
u = \Delta K_p e + \Delta K_i \dot{e} + \Delta K_d \ddot{e} + \Delta K_p + K_p' \frac{de}{dt} + \Delta K_i + K_i' \frac{\dot{e}}{dt} + \Delta K_d + K_d'
\]

(2)

\( K_p' \), \( K_i' \) and \( K_d' \) are the initial values of the PID controller. The fuzzy PID control algorithm can adjust the value of the PID parameter in real time. The control accuracy of the controller is significantly improved.

3. Control system experimental research

This experiment uses DSPACE system to build a software and hardware platform. This system can be seamlessly connected with MATLAB/Simulink to realize semi-physical and semi-simulation control experimental research. In this experiment, two pneumatic muscles are used to drive the joint rotation.
Each pneumatic muscle is controlled by an SMC solenoid valve, and the joint angle is measured by an angle encoder [8]. Figure 5 reveals the experimental system platform.

![Fig.5 control system platform](image)

Since the hip joint and the knee joint are respectively driven by two pneumatic muscles, the joint rotation angle has a certain range[9-10]. After experiments, the angle of the double pneumatic muscles to pull the hip joint ranges from -60° to 60°, the voltage signal is 0-5V; the angle range of driving the knee joint from -70° to 70°, and the voltage signal is 0-1.5V. If the control signals of the solenoid valves that control the two pneumatic muscles are given separately, it will lead to the situation that the control model of the system is difficult to obtain, so set equation (3)

\[
\begin{align*}
    u_1 + u_2 &= 1.5 \\
    u_3 + u_4 &= 5
\end{align*}
\]

which is equation (4)

\[
\begin{align*}
    u_1 &= 1.5 - u_2 \\
    u_3 &= 5 - u_4
\end{align*}
\]

\[u_1\] and \[u_2\] are the control signals of the knee joint control solenoid valve, \[u_3\] and \[u_4\] are the control signals of the hip joint control solenoid valve, so that each joint only needs to give a control signal, set the knee joint control signal \[u_1 = u_3\], hip joint control signal \[u_2 = u_4\]. Figure 6 reveals the relationship between the control signal and the joint output angle after experimental measurement. The equation (5) was obtained by data fitting

\[
\begin{align*}
    u_1 &= 0.04544\theta + 3.004 \\
    u_2 &= 0.008544\theta + 0.9533
\end{align*}
\]

[8] Yuan et al., 2019

[9] Li et al., 2018

[10] Wang et al., 2017
In the above experiments, the process of controlling the voltage signal was a slow process, and the obtained experimental results could be regarded as a static relationship curve. Using the model fitted by this data as the reference control of the feedforward signal, the function of quickly reaching steady state could be realized. The control model shown in Fig.7 was built in Simulink, and the lower extremity exoskeleton gait trajectory follow-up experiment was performed. Figure 8 and figure 9 reveals the follow-up effect of the hip joint and the knee joint.

It can be seen from figure 8 and figure 9 that the fuzzy PID control algorithm can achieve better tracking effect in hip and knee joint control. There was an obvious fact for the hip trajectory follow that the follow track can follow the expected trajectory well after 0.4s (Fig.9). This study also showed a significant fact that knee can track the expected trajectory better than the hip (Fig.10). The following error is between -5° and 5°. There is a certain following hysteresis effect in places where the joint angle changes rapidly. If the period of the desired trajectory is increased, the hysteresis effect can be reduced.

3.1 View the pre-formatted styles
When doing human body wear experiments, an angle sensor was installed at the joints of the lower limbs of the human body for detecting the angular change during the swinging of the lower limbs of the human body, and as a reference value for joint rotation, the joint movement of the human body is realized. The wearer is 175mm tall and weighs 65kg. The human body wear swing process and knee joint angle sensor was shown in Fig.10. From the experimental results in Figure 11, the human body had a good follow-up effect when did the human body wear experiments.
In the human leg swing follow-up experiment, the mechanism can follow the angular movement of the human body at random swings. A slight amount of jitter during the swing, but the following error can also be controlled within ±5°. Due to some errors in the experimental platform, the results indicated that the swing based on fuzzy PID control was higher control precision and stability than traditional PID.

4. Conclusion
A lower extremity exoskeleton leg based on pneumatic muscle-driven was developed. Combined with DSPACE semi-physical and semi-simulation system, a fuzzy adaptive PID controller was designed. swing experiments of the lower extremity exoskeleton leg was implemented. The results of the experiments showed that the fuzzy adaptive PID controller was designed in this paper had a good effect coordination capability between the hip joint and knee joint during swing motion. Future research will investigate frequency adaptation capability and effectiveness of control method for using the lower extremity exoskeleton walking.

5. References
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