COMPARISONS BETWEEN ADAPTIVE FUZZY CONTROLLER, IMPEDANCE CONTROLLER AND PID CONTROLLER FOR LOWER EXTREMITY REHABILITATION EXOSKELETON

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SUMMARY

The study proposes an intelligent lower extremity rehabilitation training system controlled by adaptive fuzzy controllers (AFCs) and impedance controllers (ICs). The structure of the robotic leg exoskeleton can be divided into three parts including hip joint, knee joint, and ankle joint, which are driven by linear actuators and pulleys. Therefore, the movement of the robotic leg exoskeleton can be controlled by driving the linear actuators. The results of simulation reveal that the design of the proposed controllers presents good performances and effectiveness.Finally, comparisons between the above controllers and PID controller are also made.

Keywords: *adaptive fuzzy control,impedance control, PID, exoskeleton, rehabilitation, Simmechanics simulation*

INTRODUCTION

Scientific and technological work on exoskeletons began in the early 1960s, but only has recently been applied to rehabilitation and functional substitution in patients suffering from motor disorder [1]. After brief and unsuccessful attempts in these years, advances in sensing, actuation and computing technologies have renewed the confidence in the viability of developing an autonomous exoskeleton system for human performance augmentation. Not only do these advances permit the realization of more compact, lightweight and robust robotic hardware design, but they also permit the development of increasingly sophisticated control laws in terms of both real-time processing capability and design and analysis computer aided tools [2-5].The proposed robotic leg exoskeleton is configured with either a powered treadmills or a mobile platform to provide various rehabilitation purposes. The exoskeleton is comprised of two anthropomorphic legs and spine that provides a versatile loading interface. The device has been designed and controlled in such a way that the human can conduct a wide spectrum of activities without feeling the device.The future possible applications of exoskeletons are endless and include construction workers, earthquake rescue personnel, space exploration, and physical rehabilitation. Currently, the demand of health care is the strongest need in the modern society.

This paper aims at comparing AFC, IC with PID in order to emphasize effectiveness and accuracy of the proposed controllers.

STRUCTURE OF EXOSKELETON SYSTEM

The exoskeleton system includes two legs, one treadmill, and one suspension bar as shown in Figure 1. Legs of the exoskeleton are designed with ability to adjust the length of thigh and shin to fit every patient.

The hip angle, knee angle and the ankle angle will be driven by linear actuators and pulley as shown in Figure 4.

The schematic diagram of exoskeleton system is shown in Figure 2 in whicha set of five coordinate systems (CSs) includes one Reference CS and four CSs of four joints (prismatic hip joint, revolute hip joint, knee joint, ankle joint).

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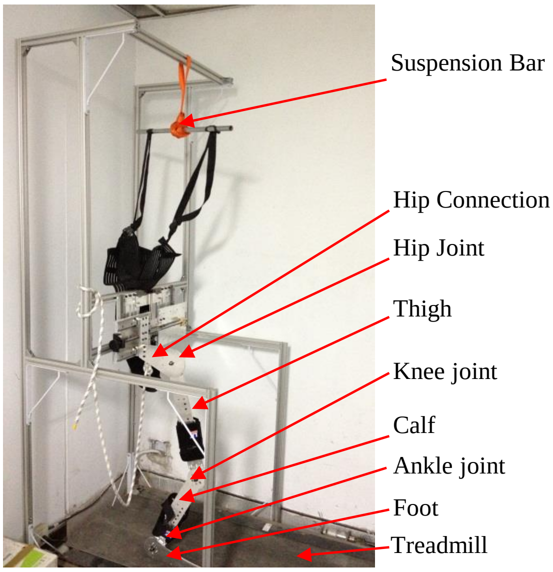

Figure1. *Structure of the Exoskeleton*

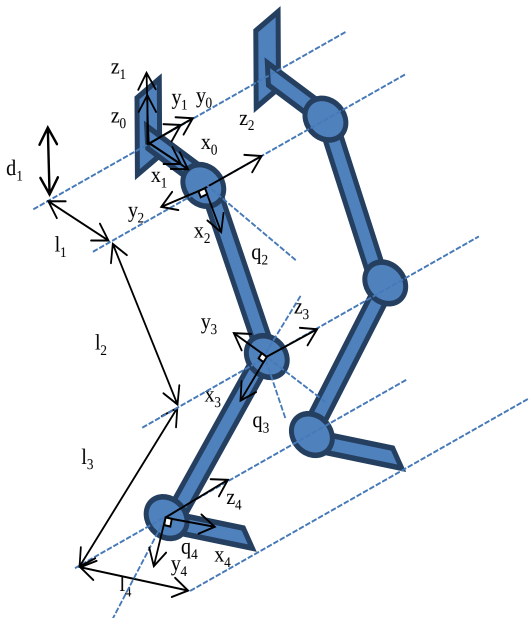

Figure 2. *Schematic diagram of exoskeleton system*

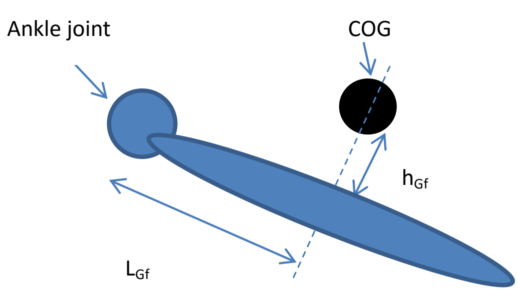

Figure 3. *Pedal and parameters*

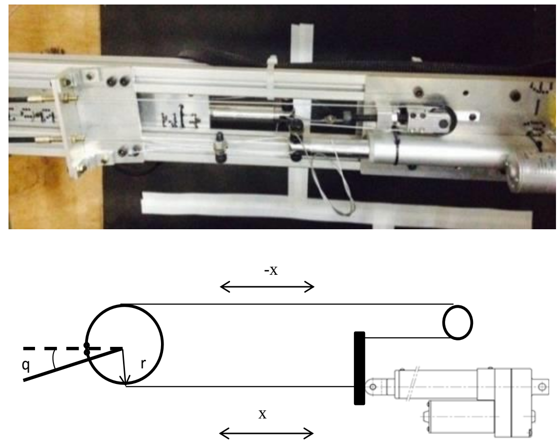

Figure 4. *One pulley driven by one linear actuator*

The mathematical equation system of the ankle joint as follows [6]:

$$\ddot{x}_2 = f(x_1) + g(x_1)u \tag{1}$$

$$f(x_1) = \frac{-g(X_4 \sin(x_1) + Y_4 \cos(x_1))}{J_4} \tag{2}$$

$$g(x_1) = \frac{1}{J_4} \tag{3}$$

$$x_1 = q_4; x_2 = \dot{q}_4; u = T_4; y = x_1 \tag{4}$$

$$X_4 = -m_f h_{Gf}; Y_4 = m_f L_{Gf} \tag{5}$$

$$J_4 = I_f + m_f (h_{Gf}^2 + L_{Gf}^2) \tag{6}$$

$$\ddot{q}_2 = \ddot{q}_3 = 0 \tag{7}$$

$$\dot{q}_2 = \dot{q}_3 = 0 \tag{8}$$

where:

+ q_2, q_3, q_4 are angular angles of the hip joint, knee joint and ankle joint respectively.

+ T_4 is the torque need to be exerted on the ankle joint.

+ x_1 and x_2 are state variables of the ankle joint.

+ h_{Gf} is the distance from the foot (pedal) to the center of gravity of the foot (COG) as shown in Figure 3.

+L_{Gf} is the distance from the ankle joint to COG along the pedal as shown in Figure 3.

+ m_f is the mass of the foot.

+ J_4 is the inertia torque of the foot.

CONTROL METHOD

Having been mentioned in [9], the impedance controller (IC) can be applied to control the hip joint angle, knee joint angle, and ankle joint angle independently with block diagram as shown in Figure 5. G is the transfer function of the exoskeleton and G' is an estimate of the machine forward dynamics. T_h denotes the torque exerted on the exoskeleton by human. T_a denotes the torque exerted by actuator. K is a PD controller. K_h is the impedance between the human and the machine, q_h is the human's position, and q is the machine's position.

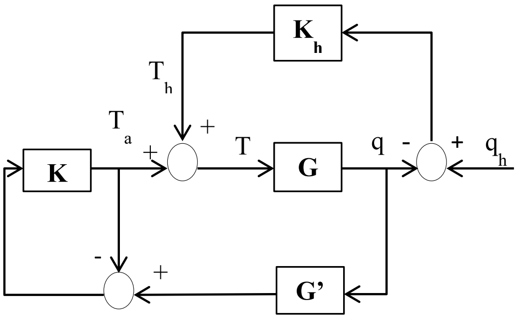

Figure 5. *Block diagram ofIC*

The rehabilitation exoskeleton system involves plenty of uncertainties and the lack of information. Accordingly, AFCs that have been proposed in [10] make the system enable to walk autonomously as a human regardless of the existence of unknown parameters. Calculations of the ankle joint controller depend on mathematical equations (1-8) in associated with the control scheme as shown in Figure 6. Actually, *f(x)* and *g(x)* are unknown; therefore, designers need to estimate values of them.

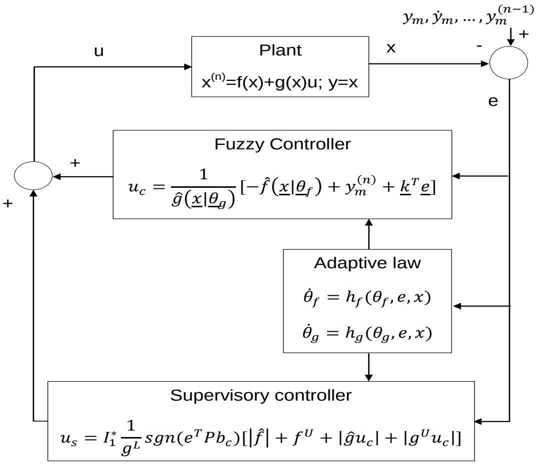

Figure 6. *Block diagram of AFC*

These estimated valuesdenoted by $\hat{f}(\underline{x}\,|\,\underline{\theta}_f)$ and $\hat{g}(\underline{x}\,|\,\underline{\theta}_g)$ will be obtained by the adaptive law and the fuzzy basic function [7].

SIMULATION RESULTS

Firstly, there is an assumption that the prismatic joint movement does not affect the revolute joint movement. In addition, the mathematical model of the ankle joint is applied to other joints. Matlab has been used to simulate the adaptive fuzzy control method. The mathematical model and Simmechanics modelare used to demonstrate howthe adaptive fuzzy controllers and the impedance controllers work in the exoskeleton system. Besides, two types of the input applied to the system are the sinusoidal signal and target trajectory. Specifically, the target trajectory is a data packet that is collected from normal human walking experiments in the laboratory. The packet is comprised of the angle data of the hip, knee and ankle joints when a human walks on a treadmill. After being collected, the raw data is filtered to remove noise in order to have a smooth form. Therefore, the system using the target trajectory can help paralyzed patients walk normally.

In order to make explicit comparisons among these controllers, only the hip joint performance is mentioned in this paper. The mathematical model of the ankle joint shown in equation (1) and AFC block diagramare used to design and simulate the hip performance that is demonstrated in Figure 7. It can be seen thatactual positions follow desired positions and the maximum error is about 0.0009 rad. Figure 8 reveals the result obtained by IC. It is evident that the maximum error in this case is about 0.0006 rad. These tiny errors refer to an accurate tracking performance of both above controllers. In Figure 9, the maximum error of the PID controller is about 0.004 noticeably bigger than that of two controllers [11].

When a heavy load is applied to the model, performances of IC and AFC are demonstrated in Figure 10 and Figure 11 respectively.

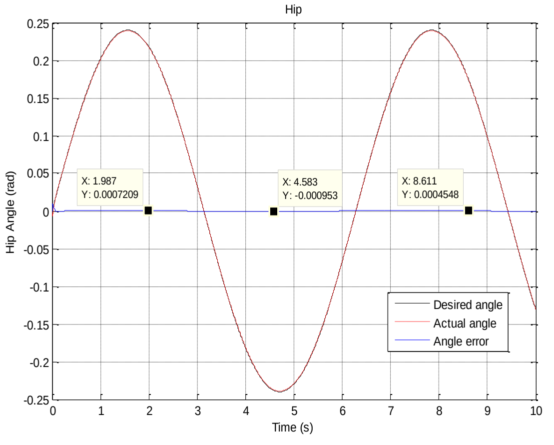

Figure 7. *Hip performance with AFC*

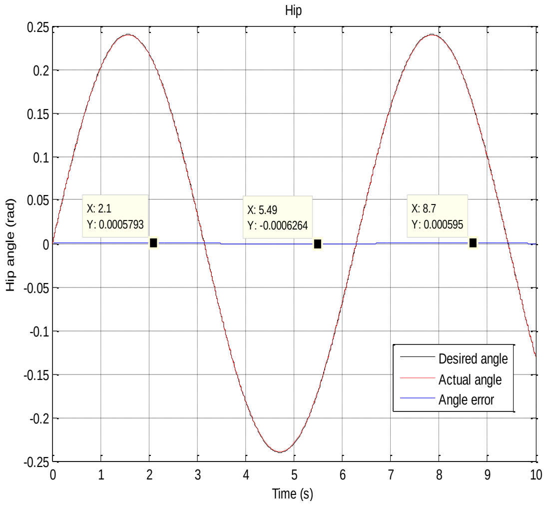

Figure 8. *Hip performance with IC*

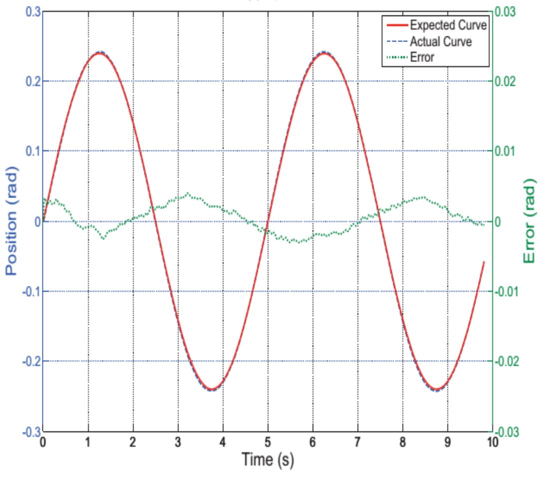

Figure 9. *Hip performance with a PID controller [11]*

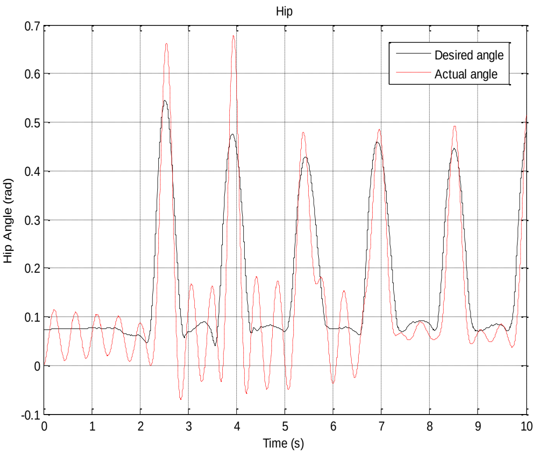

Figure 10. *Hip performance with IC*

It is clear that AFC enables to adapt to load changes in order to have better performance than that of IC.

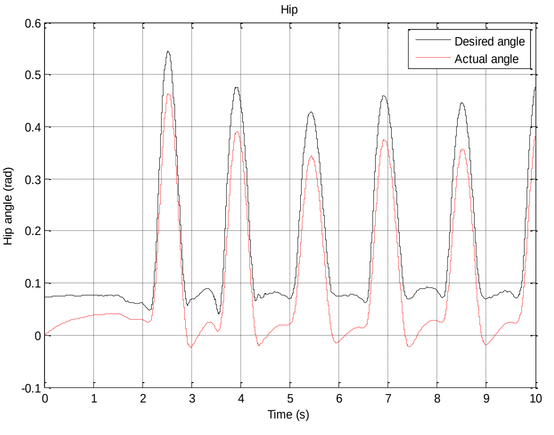

Figure 11. *Hip performance with AFC*

CONCLUSIONS

In this paper, AFC and IC used to drive each joint in robotic leg exoskeleton shows its significant advantages in comparison with PID controllers. In addition, AFC have a better adaptation with heavy load than that of IC. Moreover, it should be re-emphasized that the intelligent lower extremity rehabilitation training system proposed in this paper can achieve good performance and effectiveness. In the future, this system should have a combination between controllers and the central nerve system of patients to provide a series of intelligent rehabilitation programs for the elderly and muscle disease patient rehabilitation.

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TÓM TẮT

SO SÁNH BỘ ĐIỀU KHIỂN MỜ THÍCH NGHI, BỘ ĐIỀU KHIỂN TRỞ KHÁNG VÀ BỘ ĐIỀU KHIỂN PID SỬ DỤNG TRONG BỘ XƯƠNG NGOÀI PHỤC HỒI CHỨC NĂNG CHI DƯỚI

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Nghiên cứu này đề xuất hệ thống phục hồi chức năng thông minh cho chi dưới được điều khiển bởi các bộ điều khiển mờ thích nghi và các bộ điều khiển trở kháng. Cấu trúc của robot chân này có thể được chia làm 3 phần bao gồm khớp hông, khớp đầu gối và khớp mắt cá chân. Tất cả các khớp này được dẫn động bởi các thiết bị chấp hành tuyến tính và puli. Do đó, chuyển động của robot chân có thể được điều khiển bởi truyền động các thiết bị chấp hành tuyến tính này. Kết quả mô phỏng chỉ ra sự hoạt động tốt và hiệu quả của các bộ điều khiển được nêu trên. Cuối cùng, các bộ điều khiển được so sánh với nhau và được so sánh với bộ điều khiển PID.

Từ khóa: *Điều khiển thích nghi, điều khiển trở kháng, PID, bộ xương ngoài, phục hồi chức năng, mô phỏng Simmechanics*

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