






An FES-Cycling Control System Based on Crank Angle

Tingting Wang^{1,4} , Xuqun Pei^{2,4} , Min Liu^{3,4}, Chengqian Wang^{1,4} ,
Mingxu Sun^{1,4}, and Han Zhang^{1,4}

¹ School of Electrical Engineering, University of Jinan, Jinan 250022, China
202021100395@mail.ujn.edu.cn

² Jinan Central Hospital, Jinan 250000, China

³ Shandong Provincial Third Hospital, Jinan 250000, China

⁴ Shandong Betr Medical Technology Co. Ltd., Jinan 250022, China
13370582962@163.com

Abstract. Functional Electrical Stimulation (FES) cycling system is beneficial to the rehabilitation of patients with Spinal Cord Injury (SCI). In this paper, an FES cycling control system based on angular switching of electrical stimulation phases was developed using an indoor cycle, an electrical stimulator, a wireless inertial sensor and a PC. Then, this system was tested by healthy subjects. The device was able to send feedback data on the angle of the crank in real time to a PC, which processed the acquired data and sent serial data to the electrical stimulator to control the switching of the electrical stimulation phases. The electrical stimulator was configured in different set-up files by testing the muscle tolerance of the volunteers. Under the set experimental mode, at different crank angles, the target muscles are given appropriate stimulation pulses by the electrical stimulator. The electrical stimulation pattern: the quadriceps and biceps femoris of the volunteers were given alternate stimulation patterns. In the experiment, two healthy volunteers were tested at 3 different cycling speeds of 0.6 lap/sec, 1 lap/sec and 2 lap/sec. The test results show that the function and implementation of the controller are successful.

Keywords: Cycling · Lower limb · FES

1 Introduction

Spinal cord injury is the most serious complication of Trauma, often leading to severe dysfunction of the limbs below the injured segment. Specifically, spinal cord injuries can severely affect the ability to perform functional movements such as standing, walking or cycling. In the United States, approximately 291,000

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people have spinal cord injuries [1]. This disease not only causes physical damage such as physical impairments of the patient's limbs, motor dysfunction, but also brings severe psychological pressure to the individual, which also has a great impact on its return to society. For patients with spinal cord injury, preventing muscle atrophy is a key factor, and it is necessary to train the affected side muscles. Studies have shown that FES is one of the most effective ways of muscle recovery [2]. FES technology uses electrical stimulation to activate paralyzed or paralyzed muscles with precise stimulation sequence and stimulation intensity [3], so that patients with spinal cord injury can restore certain motor functions.

Stimulating the leg muscles to achieve cyclic movements is much easier to achieve than using FES to achieve movements such as standing and walking. The FES cycling system is designed to achieve cyclic movements of the lower limbs by sequentially stimulating the patient's large muscle groups (including the quadriceps, gluteus, hamstrings and other muscles of the leg) and controlling the knee and ankle joints. By selecting the appropriate stimulation pattern, FES pedal exercise helps spinal cord injury patients to replenish muscle fatigue and increase rehabilitation training time [4,5]. And it can be used to prevent muscle atrophy during inactivity and aging, making it possible to repair muscle damage caused by various muscle diseases [6]. The system consists of four main components: the stimulator, the mechanical device, the controller and the signal acquisition equipment.

The effect of FES on cardiorespiratory function was proposed by Faghri PD et al. in 1984 [7]. This system was the prototype of the FES pedal cycle and has since attracted more attention from researchers. Various scholars have looked at the FES cycling in terms of improvements in physical function and have concluded that the FES cycling system has improved cardiopulmonary function, leg muscle recovery and bone density in patients [8–10]. In the field of FES cycling control systems, in 1997 Chen et al. Document [11] applied fuzzy control theory to the study of FES cycling system controllers for on-line real-time control of system parameters. In 2001, Gföhler et al. Document [12] looked at the effects of the geometry of the cycling not only in terms of the independent parameters used to generate moments, but also in terms of individual differences of paralysed patients. Kugima et al. Document [13] proposed a FES cycling system for speed tracking control of human limbs, modelled Lagrangian dynamics and analysed its stability using Lyapunov's method. Cousin et al. Document [14,15] applied admittance control to the FES loop control system. There are also more constraints required for a control system that is too complex in realising a simple rehabilitation exercise process. This paper therefore proposes a simple control system for the FES cycling.

In this paper, in order to test the simple FES cycling control system, referring to T. Watanabe et al. proposed a FES control system that triggers electrical stimulation by the accelerometer signal attached to the crank [16] and Mingxu Sun et al. proposed the finite state machine [17]. Use the wireless inertial sensor to directly measure the crank acceleration to switch the stage of controlling the electric stimulator. By limiting the speed, two healthy volunteers were allowed

to perform the FES cycling control system proposed by the FES cycling exercise test. Finally, the state transition of the electric stimulator was analyzed.

2 Overview of the FES Cycling Control System

2.1 The Components of the FES Cycling Control System

The FES cycling system consists of an electrical stimulator, a cycle and a wireless inertial sensor, each of which is described below.

Stimulator. The FES cycling rehabilitation system can switch the working phase of the electrical stimulator through the crank angle. Electrical stimulation has the characteristics of expandable channels, programmable and portable. Electrical stimulator are divided into master and slave, which have the advantages of small size and light weight. Main control: 13 cm * 10 cm * 2 cm, slave electrical stimulator: 6 cm * 5.5 cm * 1.5 cm. It is powered by a rechargeable lithium battery, and the stimulation parameter 20 Hz. The biphasic pulse width is between 0–180 us, and the intensity is adjustable within the range of 0–100 mA. These stimulating pulses are in direct contact with the target muscle through the electrode sheet, and the pulse is input to the muscle and the muscle is contracted to complete the target action. If the three channels of the master control cannot reach the required number of channels, the number of channels can be expanded by expanding the slave electrical stimulation.

Cycle. Use a fixed stationary cycle for testing. This cycle has a simple structure, so that the results can be better affected by external interference during the test process (for example, the resistance caused by the chain and the resistance caused by the friction between the wheel and the ground, etc.); in the static state, it reduces the accident.

Wireless Inertial Sensor. Since it is required to switch the next stage of the electrical stimulator according to the real-time angle, there are certain requirements for the receiving speed of the angle data. If the inertial sensor in the electric stimulator is used to transmit data directly, the bicycle movement is restricted by the wired condition of the serial port. Therefore, use the WIFI nine-axis sensor to collect the crankshaft angle data and transmit it to the control system using the User Datagram Protocol (UDP). UDP is a connectionless protocol, and data communication can be realized only by the application and the receiving end in a local area network. At the sending end, the speed of UDP transmission of data is only limited by the speed at which the application program generates data, the capacity of the computer, and the transmission bandwidth; at the receiving end, UDP puts each message segment in a queue, and the application reads it from the queue every time A message segment. According to the above characteristics of UDP, it meets the requirements of real-time communication. The

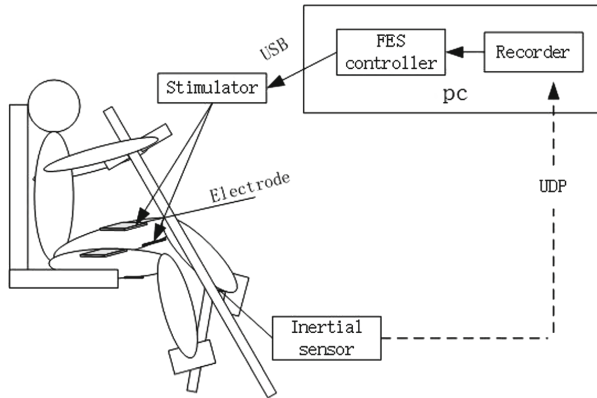


Fig. 1. The outline drawing of a cycle with FES control system. One of the electrodes is attached to the quadriceps and the other to the biceps.

outline drawing of a cycle with FES control system is shown in the Fig. 1. Fix the wireless inertial sensor on the center of the left crankshaft of the cycle with tape. The angle and angular velocity signals are measured by the inertial sensor, and the data of the inertial sensor is read to the PC through the UDP protocol. The timing of the electrical stimulator switching state is determined by the crank angle. Using the expandable electrical stimulator based on our previous research and development, the muscles are automatically electrically stimulated through the electrode pads at the appropriate time selected. The stimulus data is transmitted from the PC to the expandable electric stimulator through the serial port. The electric stimulator selects the state according to the received signal, thereby generating the stimulation pulse with the pulse frequency, pulse amplitude and pulse width suitable for the location. The output channel is composed of three channels of the master and one channel of the slave.

2.2 Experimental

Before the experiment, the volunteers' muscle tolerance was tested through the test mode of the electrical stimulator. Then configure the electrical stimulator with a profile suitable for volunteers. Also, before the experiment, the volunteers were told to subjectively control the riding speed of the FES bicycle at approximately 0.6 laps/sec, 1 lap/sec, and 2 laps/sec. Each FES riding exercise time exceeds 30 s, and the 30 s data with stable speed is taken during analysis.

Experimental Subjects. The subjects of this study included a 25-years-old healthy male and a 23-years-old healthy male.

Experimental Environment. We choose a wide and comfortable indoor environment as the test site. During the test, two healthy volunteers performed cycle

exercises of 0.6 laps/sec, 1 laps/sec, and 2 laps/sec, and recorded data such as the crank angle of the bicycle. Channel 1, channel 2, channel 3 and channel 4 of the electrical stimulation stimulate the right quadriceps, left quadriceps, right biceps femoris and left biceps femoris respectively. The physical map is shown in the Fig. 2.

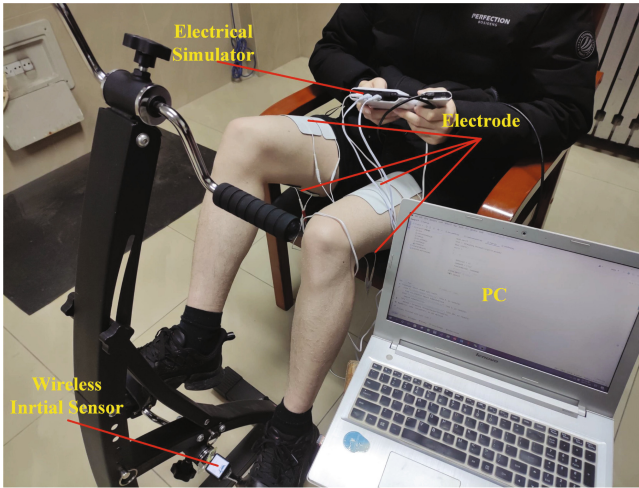


Fig. 2. FES cycling control system.

Experiment Methods. In this paper, we use the stimulation mode: quadriceps and biceps femoris stimulation alternately. The quadriceps is the thigh muscle of the human body, located in the front of the thigh muscle, with the function of extending the knee joint and bending the hip joint. The biceps femoris is one of the posterior muscles of the thigh and has the function of the knee joint. During the experiment, quadriceps and biceps femoris were alternately stimulated by electric stimulator to achieve the extension and flexion of the knee joint. The right quadriceps and left biceps femoris were stimulated and defined as phase 1, and the left quadriceps and right biceps femoris were stimulated as phase 2. Transitions of phase 1 and phase 2 are triggered by suitable methods. The structure of the left and right cranks on the horizontal plane is shown in Fig. 3.

The initial state is set as the left crank is on the top, the right crank is on the bottom, the left foot is pedaling forward as the movement direction, and the initial position of the electrical stimulator is phase 1. When the receiving crank Angle is greater than or equal to 130° , the electrical stimulator performs phase 2. When the receiving crank Angle is greater than or equal to 310° , the electrical stimulator performs phase 1. Phase 1 and phase 2 correspond to left pedal and right pedal respectively. Considering that in the case of convulsion of lower limbs, the method of triggering phase transition with a reading will cause instability of the controller.

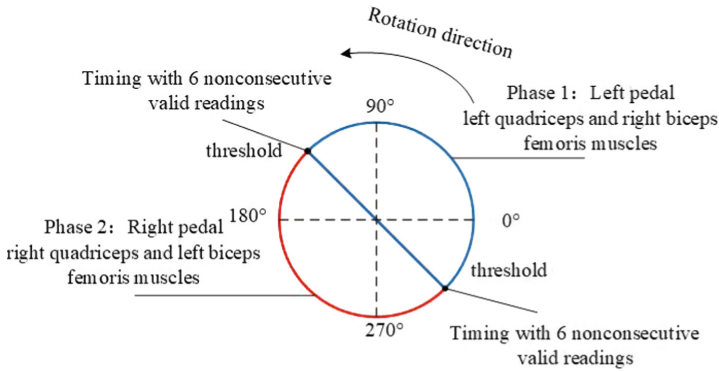


Fig. 3. Structure diagram of left and right cranks on horizontal plane. Blue line and red line symmetrical. (Color figure online)

The method of timing 6 discontinuous effective readings can better deal with the noise impact of upper limb convulsion [16]. Therefore, the triggering method in this paper is to start the effective count when one point reaches the threshold, automatically skip the no count when the number that does not reach the triggering condition in the count, and start the transition phase when the effective count reaches 6.

Implementation flow chart of FES controller is shown in Fig. 4. The initial state is set with the left crank on the top, the right crank on the bottom, and the forward cycling with the left foot as the direction of movement. The right quadriceps and the left biceps femoris muscles are stimulated first. When the received crank angle is between 310–130, the right quadriceps and left biceps femoris muscles (phase 1) are stimulated by the electrical stimulator and left pedal. When the received crank angle is between 130 and 310, the left quadriceps and right biceps femoris muscles (phase 2) are stimulated by the electrical stimulator and right pedal.

Results. During the volunteer FES cycle exercise, the relationship between the cycle exercise time and the crank angle at different speeds is shown in Fig. 5 and Fig. 6. It can be seen from the figure that within 30s, under different speed conditions, there are two phase transition points in a cycle.

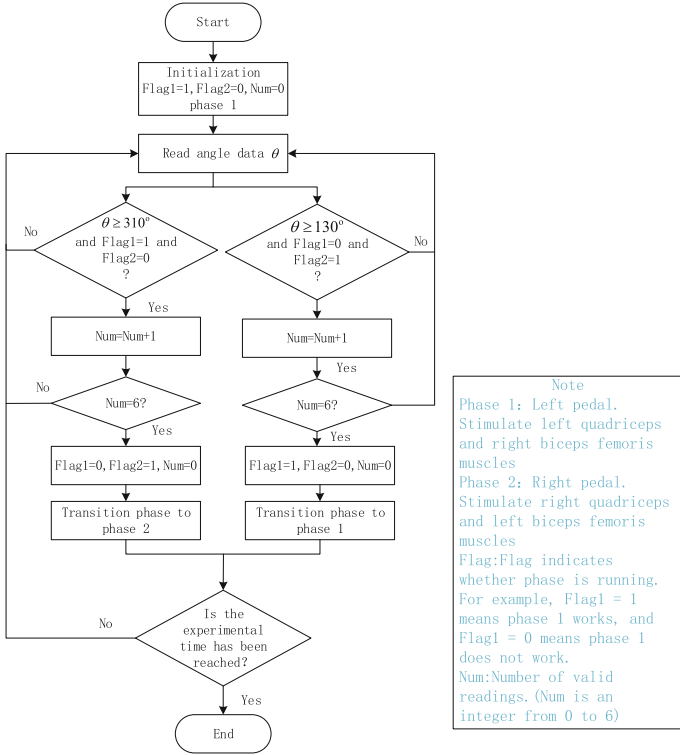


Fig. 4. Implementation flow chart of FES controller.

It can be concluded that the proposed FES cycling control system can transition points following the crank angle and stimulate the corresponding thigh muscles. In order to more intuitively observe the phase switching, we intercepted the data of two volunteers riding for two cycles in FES. It can be seen in Fig. 5 that the speed of volunteer 1 in the first two turns was not very stable. We used the data of the third and fourth cycles and the corresponding electrical stimulator channel pulses. Volunteer 2's speed was relatively stable. We used the data of the second and third cycles and the corresponding electrical stimulator channel pulses. Figure 7 and Fig. 8 show the controller phase transition of two volunteers during two cycles of FES cycle. In the figure, the transition time from the phase 1 to the phase 2 and from phase 2 to phase 1 corresponds to the transition between phase points. Moreover, in order to make the control system more stable, six discontinuous effective readings are used as the state transition condition. Therefore, the phase transition has a certain delay for the threshold point.

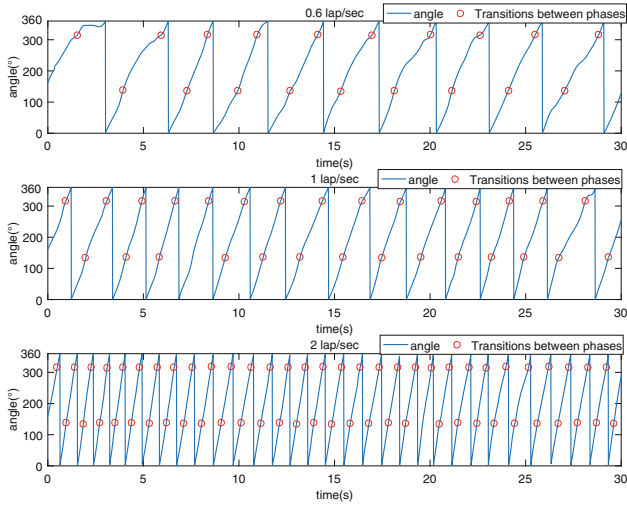


Fig. 5. Volunteer 1's FES cycling in 30s. The first point is switched from phase 1 to phase 2, the second point is switched from phase 2 to phase 1 and so on.

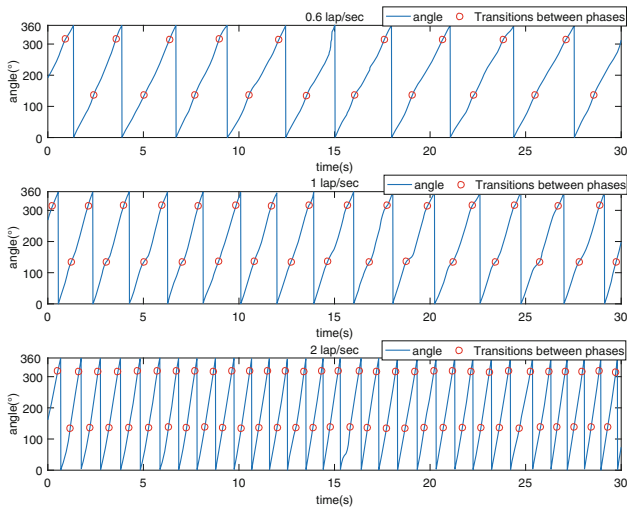


Fig. 6. Volunteer 2's FES cycling in 30s. The first point is switched from phase 1 to phase 2, the second point is switched from phase 2 to phase 1 and so on.

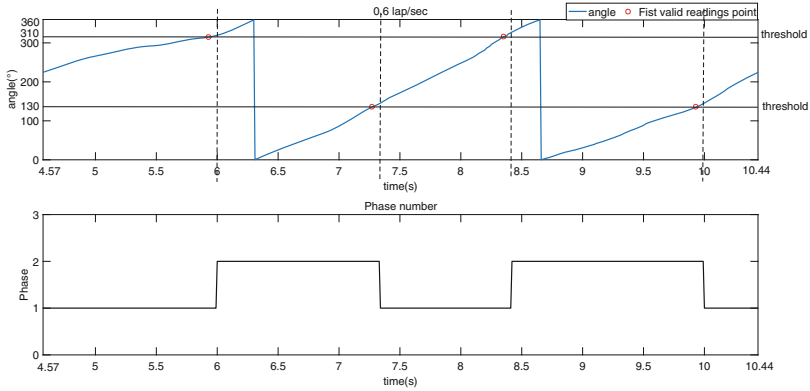


Fig. 7. Pulse waveform output from four channels of the electrical stimulator (take two cycles of the volunteer 1’s FES cycling).

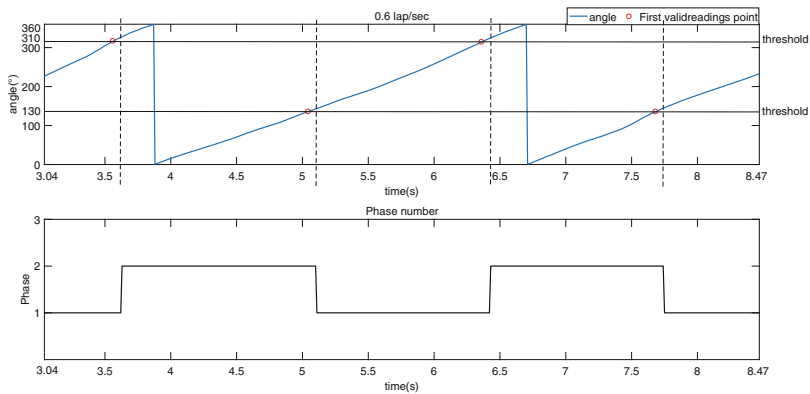


Fig. 8. Pulse waveform output from four channels of the electrical stimulator (take two cycles of the volunteer 2’s FES cycling).

3 Conclusion

This paper first gives a brief introduction to the current research status and system composition of the FES cycling system, and then proposes a method of electrical stimulation mode applied to the FES cycling and conducts experiments. The experimental results show that the response of the FES cycling control system based on the electrical stimulation mode is timely and stable in operation. However, there will be some shortcomings in the system, for example, the testers in this experiment are healthy people, not tested on patients with spinal cord injury, so the system will have some shortcomings, and the next step will be to continue to improve the system with the actual situation of the patients.

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