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Functional electrical stimulation-based cycling assisted by flywheel and electrical clutch mechanism: A feasibility simulation study

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HIGHLIGHTS

- A flywheel and electrical clutch assist mechanism is used in FES-cycling exercise.
- Fuzzy logic is used to control stimulation intensity on quadriceps in FES-cycling.
- The new mechanism suppresses speed fluctuation and reduces the cadence error.
- The new assist mechanism promotes prolonged FES-cycling and extended work rate.
- The fatigue monitor shows 14%–17% delay in muscle fatigue using the new mechanism.

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ABSTRACT

A new assist mechanism, represented by a flywheel and an electrical clutch, is developed and evaluated, in simulation studies, to assist paralysed legs during functional electrical stimulation (FES)-based cycling exercise in a closed-loop control configuration. The flywheel is engaged and disengaged, by the clutch, to assist or retard the cycling when necessary. The flywheel engages with the crank to absorb the surplus energy, produced by stimulating the leg, store it as kinetic energy and slow down the movement. Also, it engages again to use the same stored energy to assist the leg and speed up the cycling. A comparative assessment of FES-cycling, using fuzzy logic control, is carried out with and without the new assist mechanism. Clinically recorded data is used to derive a force-drop indicator for assessment purposes. Although the stimulation intensity is slightly increased, the indicator showed 14%–17% muscle fatigue delay with the new mechanism as compared with cycling without assistance. This mechanism is promoting prolonged FES-cycling and increased work rate for paraplegics by delaying the occurrence of muscle fatigue.

1. Introduction

Functional electrical stimulation (FES) is a technique of supplying a train of electrical stimuli to trigger nerves of paralysed muscles to provide muscle contraction and produce useful functional movement [1]. Several FES-based devices have been developed and utilized for therapeutic and function restoration purposes. For example, the pacemaker, as a heart pulse regulator, is used by more than 500,000 people every year [2]. Also, FES has been utilized to provide lower extremities' movement for people with complete and incomplete spinal cord injuries in an attempt to restore locomotion through different exercises such as walking, standing and cycling. Muscle stimulation with FES can be done either by using implanted electrodes [3,4] or by surface electrodes mounted on the skin. Stimulation with surface electrodes is easier, cheaper, non-invasive, and has no potential of infection as compared with other types [5].

FES-based cycling is a type of exercise that employs FES signals to stimulate leg muscles of paralysed people in a specific sequence to perform pedalling motion. FES-cycling is more beneficial for a disabled person than weight lifting, although it provides smaller increase in muscle size. The cardiac output of paralysed individuals during weight lifting induced by FES produces 7 l/min while the cardiac output has been shown to rise to 15 l/min during FES-cycling exercise [6–8]. Also, several studies have shown that continuous FES-cycling exercise for paralysed people increases the cardiovascular and cardiorespiratory fitness, blood circulation in lower limbs, reverse muscle atrophy, prevention of bone loss as well as it improves the self-image of the disabled [9–13].

One of the handicaps that affect the performance and the smoothness of FES-assisted cycling is the dead points, i.e. the two points on the pedalling cycle at which it is difficult to produce sufficient torque to rotate the crank. By means of inertia and a complex

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interplay of muscle actions, healthy people can overcome these points, while it is difficult to produce such muscle actions by means of FES because the muscles involved are too deep to be stimulated by surface electrodes [14].

Previous studies have shown several attempts to overcome the dead points and produce smooth, i.e. with no abrupt change in crank velocity, FES-cycling for paraplegics. These have included improving the ergometer's mechanical design using different assist mechanisms. Some researchers have utilized an auxiliary motor to help the leg pass the dead spots and continue the cycling in case muscle fatigue occurs, and also to retard the movement by imposing braking when necessary [15–17]. Other researchers have modified the five-bar linkage of a tricycle into a four-bar linkage by using a coupler and a lever arm to eliminate the dead spots during cycling [14,18] with a drawback of eliminating the freewheeling of the tri-cycle. While Ref. [6] recruited a non-paralysed healthy person, using a modified tricycle of two side-by-side seats, to provide pedalling assistance for a paraplegic to propel the vehicle, pass the cycling dead spots and continue the cycling in case of muscle fatigue, others have added an arm-crank to the ergometer to assist the leg and provide a hybrid exercise mechanism [5].

Besides the assist mechanisms, researchers have stimulated different combinations of muscles to provide leg extension and flexion action. Some researchers have stimulated the quadriceps and hamstring of both legs [19]. Others have used the quadriceps, hamstring and the glutaeus maximus muscles [5,6,17,20,21]. While others have used the quadriceps, hamstring and the gastrocnemius muscles [15] during FES-cycling exercise.

Controlling the movement of paralysed limbs with FES using open-loop control strategy is particularly difficult. As several parameters differ from person to person, such as muscle response to FES, skin sensitivity and muscle's training condition, the stimulation parameters applied in open-loop systems are specific for a single user and may not produce the same performance with other persons [22,23]. Also, the procedures of determining the stimulation parameters are time consuming; trials lasted for 20–45 min to find the optimal parameters for the leg, by stimulating quadriceps only, to follow a desired trajectory [24]. Moreover, the open-loop approach cannot account for unforeseen conditions such as muscle spasm and mechanical disturbances. For these reasons researchers have focused on utilizing closed-loop control strategies to overcome the aforementioned problems [19,20,25–29]. To reduce the possible mechanical problems that might occur during FES-cycling due to several electrode wirings and in an attempt to provide more comfortable exercise by reducing the pre-cycling preparations required for locating the electrodes at their optimal locations over the skin to get optimal muscle response, Ref. [30] produced stimulation patterns, to perform coordinated FES-assisted cycling movement, based on stimulating single muscle group, the quadriceps, of each leg.

The flywheel, as an energy storage device, has been widely used in many commercial FES-cycling ergometers. It has been used to provide smoothness to the cycling and help pass the cycling dead spots for individuals able to pedal under loads [21]. Usually, disabled people encounter difficulties to pedal the crank of the ergometer due to weak leg muscles [31]. Although the flywheel is effective in assisting the cycling and reducing the energy expenditure [32], from other point of view, a fix-geared flywheel imposes extra load on the crank which in turn makes it harder for individuals of weak muscles to generate sufficient force and overcome the inertia to drive the flywheel without external assistance [21].

A hybrid kinetic energy recovery mechanism consisting of a flywheel, electrical clutch and continuously variable transmission (CVT) was designed for formula one motorsports in 2009 for the purpose of fuel consumption [33]. The flywheel is used to store the kinetic energy in the vehicle during braking, and later reuse the same stored energy to accelerate the vehicle. The test results showed the ability of the system to save up to 21% of the driving energy of the vehicle.

The use of such a mechanism has not been reported with FES-cycling application. In this work, it is aimed to implement a similar mechanism, represented by a flywheel and an electrical clutch, in an attempt to save the excessive energy in the system and make use of it to prolong the exercise. The flywheel as an energy storage device is to be used to absorb and store the surplus of kinetic energy in the system in order to retard the movement when necessary, and later reuse the stored kinetic energy to help the leg pedal and speed up the movement. The use of a clutch is necessary to provide the flywheel's engagement and disengagement to/from the crank (shaft) of the cycling ergometer.

In this work, for assessment purposes, a comparison between two approaches will be presented; the first scenario is a closed-loop control strategy for FES-cycling by stimulating single muscle group, the quadriceps, without any assist mechanism. The second scenario is a closed-loop control strategy for FES-cycling by stimulating the quadriceps with the aid of the flywheel and electrical clutch mechanism. This work is a developed version of the authors' initial work [34] through the use of fuzzy logic controllers, instead of PID, and an improved, more accurate and easy-to-implement, flywheel engagement mechanism. The new proposed approach, with a similar tracking performance, reduces the overall stimulation intensity on both legs by approximately 30% (from 685 μs to 475 μs) which consequently delays muscle fatigue and prolongs the cycling exercise.

2. System description

The use of an accurate model is important from the viewpoint of system simulation to obtain results close to reality as well as from the perspective of control design. In addition to the accuracy of the data used to build the model, the technique or the software utilized to simulate the plant behaviour plays a significant role in obtaining accurate results. In this work a humanoid–bicycle model, equipped with a flywheel and an electrical clutch mechanism, is developed using Visual Nastran 4D (Vn4D) software. The Vn4D software is selected for its ability to combine computer-aided design (CAD), motion and finite element analysis (FEA) in a single modelling system. Moreover, it is equipped with sensors, meters and controllable constraints useful for studying the behaviour of control systems in a simulation platform. Furthermore, the Vn4D software can be easily connected with Simulink/matlab software, hence allowing design and evaluation of control strategies.

2.1. The humanoid model

The quality of the humanoid model depends on the accuracy of the data used to build the model. In this work, the humanoid model is developed using the standard anthropometric human dimensions introduced by Ref. [35] as shown in Fig. 1. The length and the mass of each body segment are expressed as fraction of the overall body height and weight respectively.

The humanoid developed in this work is based on a human body of 1.80 m in height (H) and 70 kg in weight (M). The length and mass of each segment of the developed humanoid model are shown in Tables 1 and 2 respectively.

The centre of mass and the density of each segment were obtained from the same anthropometric data. The centre of mass was essential to determine the shape of each segment, while the density of each segment was used to obtain the volume and consequently the segment's width. Table 3 shows the location of centre of mass, density and volume of each segment of the developed humanoid model.