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A Comparative Study on Control Strategies for FES Cycling Using a Detailed Musculoskeletal Model

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Abstract: Although advances in technology promoted new physiotherapy approaches for rehabilitation, there is still an urge for equipment and techniques to improve quality of life for patients with motor disabilities. Functional Electrical Stimulation Cycling (FES Cycling) is an example of this type of technology, in which we control stimulation parameters to enable a spinal cord injured person to ride a bicycle. The presented research proposes a new detailed musculoskeletal platform using OpenSim to test and develop control strategies. With this platform, we were able to compare performance of four control techniques in transient and steady states.

Keywords: Neurostimulation, Assistive devices.

1. INTRODUCTION

Advances in technology promoted new physiotherapy techniques for restoration of movements in individuals with lower limbs disabilities, such as Spinal Cord Injury (SCI). Functional Electrical Stimulation (FES) stands for a well-known rehabilitation technique for motor functions improvement. It is based on the generation of muscle contraction in order to produce torque (Lynch and Popovic (2012); Martin et al. (2012)). Figoni et al. (1991) and Bélanger et al. (2000) presented FES rehabilitation vantages for SCI individuals, such as enhancement of muscle strength, decrease of bone loss, cardiovascular and respiratory improvement, and quality of life (Szecsi et al. (2014)).

Controllers in FES Cycling regulate pulses trains parameters (frequency, pulse width and current amplitude) to generate enough contraction on muscles to ride a bicycle (Ambrosini et al. (2014); Fornusek et al. (2013)), i.e., the SCI patient legs produce the mechanical work. Although feasible, the greatest challenges of this system remains in finding efficient controllers to provide the necessary stimulation for the desired torques. As electrical stimulation accelerates muscle fatigue (Ibitoye et al. (2014)), time of experiments are limited, avoiding maximum stimulation throughout the entire procedure.

Therefore, complex controllers requiring a high number of trials are still not applicable in real systems, only in simulation (Kim et al. (2008); Li et al. (2010); Peng-Feng Li et al. (2009); Kawai et al. (2014)). In these projects, researchers model cycling movements in different software for proof of concepts. The representations are usually simple and limited due to non-linearity of muscles and bones. As far as we know, there is no free available platform with a detailed musculoskeletal model for cycling.

The main goal of this paper is to provide this platform in order to compare four different control strategies for FES cycling: open loop, phase adjustment, proportional integral control and fuzzy logic control. In each controller, we applied stimulation with three sets of muscle groups: quadriceps, quadriceps and hamstrings, and quadriceps, hamstrings and gluteus.

This paper presents a simulation environment for FES Cycling in Section 2, describing the basic framework and models. In the proposed platform, we performed the four control strategies described in Section 3. We presented and discussed the results in Sections 4 and 5, the simulations suggest that the model performs better with PI Control. Lastly, we exposed our final considerations in Section 6.

2. SIMULATION ENVIRONMENT FOR FES CYCLING

2.1 Basic Framework

The basic framework of this FES Cycling Platform requires *OpenSim* and its integration with Matlab.

OpenSim The OpenSim platform is a free available, open-source software to simulate highly detailed musculoskeletal models (Delp et al. (2007)) [1]. The software provides kinematics and dynamics tools to understand and analyze motions. Using a graphical interface, users can generate simulations with default models or develop new models and controllers.

These tools measure states variables during simulations. Users can also regulate the muscle excitation in real time

[1] It is being developed in maintained in `https://simtk.org/projects/opensim`

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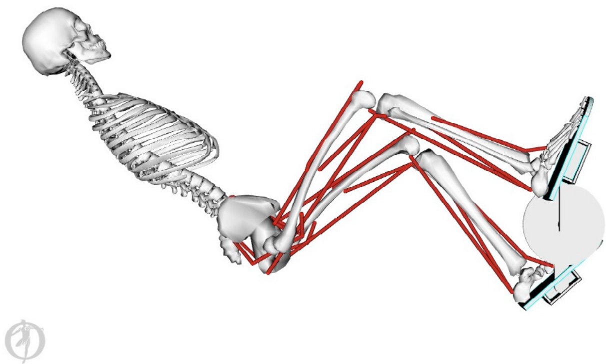

Fig. 1. Complete model for cycling positioned similar to the EMA Trike (Bó et al. (2015)). OpenSim represents muscles as red lines.

for dynamic simulation (for simplicity, we define excitation as the same as stimulation level). For FES control strategies evaluations, we use the forward dynamics tool; however, the OpenSim API only allows open loop analysis.

OpenSim integration with Matlab for closed-loop control There are also scripting environments to use OpenSim API without any requirement to set up a development environment. It is possible to access OpenSim tools to create, simulate and analyze models using Matlab.

Nevertheless, basic OpenSim scripting does not enable performing dynamic simulations to integrate closed-loop artificial controllers. In our solution, we convert OpenSim models and states to Matlab components, and perform forward dynamic simulation using Matlab tools (e.g. ode45).

2.2 Models

In order to study control strategies for FES cycling using Opensim, we need a musculoskeletal model containing involved limbs and muscles, as well as its mechanical coupling with pedals and crankset. Such models are not readily available within Opensim database. Fig. 1 illustrates the resulting model developed for this study, in which the lower limbs are attached to the foot support with pedals and crankset.

Lower limbs The Lower Limb is a default model[2] simplified for fast simulations, focused in lower extremities. The original model includes 10 degrees of freedom and 18 muscles. We locked lumbar, pelvis and ankles movements to simulate a person riding a bicycle, in which hips and knees run freely. Table 1 presents the locked positions based on the EMA Trike, developed in University at the Brasília (Bó et al. (2015)).

Table 1. Locked degrees of freedom.

DOF	Value
Pelvis Tilt	45°
Pelvis Tx	$0mm$
Pelvis Ty	$0mm$
Ankle Angle Right	0°
Ankle Angle Left	0°
Lumbar Extension Tilt	0°

[2] Available in `http://goo.gl/XSaArf`.

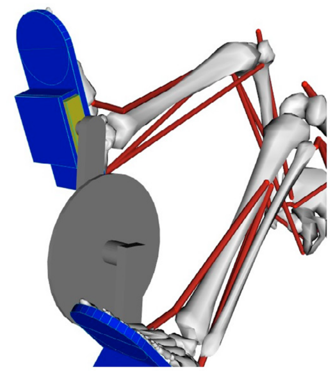

Fig. 2. Detail from the complete model focused at the foot support with pedal and crankset.

State variables of the model are position, speed and force from hips, knees, crankset and pedals. In addition, the available muscles in the model are *Hamstrings*, *Biceps Femoris Short Head*, *Gluteus*, *Iliopsoas*, *Rectus Femoris*, *Vastus Lateralis*, *Gastrocnemius*, *Soleus* and *Tibialis Anterior*.

Foot support with pedal and crankset Using the free software Blender, we added three objects to the Lower Limb model, a *drivetrain* and two *foot supports*, as shown in Fig. 2. The drivetrain is divided into *crankset* and *pedals*. The crankset can only rotate in the sagittal plane, and cannot move in translation. The length of the crankset is $78mm$. We attached each pedal ($90mm \cdot 86mm \cdot 26mm$) to the crankset at the end of the crank arms, allowing rotation along the axes perpendicular to the crank arms. The foot support immobilizes the ankles and connects the foot to the pedals through a box in which the pedal is accommodated. Consequently, the foot support transmits the force to the pedal using contact geometries (physical shapes that allow collisions in OpenSim).

3. CONTROL STRATEGIES

Cyclists with full volitional muscle control contract a set of muscles to provide necessary torques for pedal stroke. For similar cycling movements, we choose to apply coordinated excitation on the following muscle groups, based on previous work (Hunt (2005); Bó et al. (2015)):

- Quadriceps femoris: excitation of *rectus femoris* and *vastus lateralis* for knee extension;
- Hamstrings: excitation of *hamstrings* for knee flexion and hip extension;
- Gluteus: excitation of *gluteus* for hip extension.

During one pedal stroke, quadriceps provide most torque for the pedal stroke though knee extension. Hamstrings pull the feet to the top while the gluteus provide more power for knee extension. For efficient cycling, these muscle groups must be excited in specific ranges, depending on crankset angle and speed.

Part of the model analysis focuses on how the addition of muscles improves cycling efficiency. Hence, we compared the following set of muscles: (1) quadriceps only (Q), (2) quadriceps and hamstrings (QH) and (3) quadriceps, hamstrings and gluteus (QHG).