Modelling and Control of FES-Assisted Indoor Rowing Exercise

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Abstract: This paper presents the development of a model of indoor rowing exercise for paraplegics. Indoor rowing exercise is introduced as a hybrid exercise for restoration of function of lower extremities for paraplegics through the application of functional electrical stimulation (FES). Two stimulated muscle models, quadriceps and hamstrings, are developed for knee extension and flexion. A fuzzy logic control strategy is designed to control the rowing manoeuvre. Simulation results verifying the control strategy are presented and discussed.

Keywords: Indoor rowing exercise, Paraplegics, Muscle model, Fuzzy logic control.

1. INTRODUCTION

Paraplegic is a person who has complete paralysis of the lower half of the body including both legs, usually caused by damage to the spinal cord. Frequent causes of damage are trauma (car accident, gunshot, falls, etc.) or disease (polio, spina bifida, etc.). It prevents them from walking, standing and moving freely, therefore reduces the quality of life and leads to severe psychological and physiological effects. Paraplegics are at increased risk of Cardiovascular Disease, Type 2 Diabetes Mellitus and Obesity (Wheeler, et al., 2002; Raymond, et al., 1999; Andrews, et al., 1995). To reduce these risk factors, a high intensity physical activity is required through the application of Functional Electrical Stimulation (FES). FES aims to generate movements or functions which mimic normal voluntary movements and restores the functions which those movements serve (Massoud, 2007). FES-assisted indoor rowing exercise is the hybrid FES activity introduced as a high intensity, effective, safe, affordable and natural alternative for total body exercise that combines FES-assisted lower body movement with voluntary upper body movement (Davoodi, et al., 2001, 2002a, b, c).

In FES-assisted indoor rowing exercise, FES is applied to the muscles for extension and flexion of hip, knee and ankle in order to perform the rowing exercise. The development of well founded physiological based muscle model is important in obtaining smooth rowing manoeuvres. Many muscle models have been created and one of the earliest and perhaps most popular employed muscle model is the Hill model. Various modifications have been made to more accurately incorporate further complexities and increase the model's accuracy. One of the most notable muscle models was developed by Riener (Riener, 1999; Riener, and Quintem, 1997; Riener, and Fuhr, 1998; Riener, et al., 1996, 1999, 2000). The model describes the physiologically based interpretation and includes muscle fatigue and calcium dynamics. The model is composed of three parts, namely muscle activation, muscle contraction and body segmental dynamics. Muscle activation provides the activation needed by the muscle to generate force. Muscle contraction is described as a force generating properties derived by scaling a generic Hill based model whereas, the body segmental dynamics consider the passive muscle properties and equation of motion with the interaction of environment.

To achieve a smooth and well coordinated rowing exercise for paraplegics, a well structured control strategy is required. Davoodi et al. (2002c) developed a controller that automatically controls the electrical stimulation of the paralyzed leg muscles to perform the lower body part of the rowing manoeuvre with coordination to voluntarily perform the upper body part of the manoeuvre. Although a smooth rowing manoeuvre was obtained, the total stimulation per cycle was high.

The control strategy of FES-assisted indoor rowing exercise becomes more difficult as it involves a complex physiological based human muscle. The complexity of the motor system of the human muscle leads to a degree of uncertainty in a developed mathematical model for the muscle. Few control strategies tested in this study include (model-based) PID control, and the results are not very impressive, due to such uncertainty in the model. Fuzzy logic control (FLC) is thus purposed as it does not require a model of the system. In this paper, FLC is developed to regulate the electrical stimulation applied to the physiological based muscle model for FES-assisted indoor rowing exercise for restoration of function of lower extremities.

2. DESCRIPTION OF MODEL

2.1 Indoor Rowing Exercise Model.

The indoor rowing exercise model comprises of two parts, indoor rowing machine and humanoid model developed using the Visual Nastran software. The machine is designed based on the modified indoor rowing machine (Fig.1) that comprises of all basic parts of the real machine. A new seating system was developed which has high back, adjustable backrest and adjustable belt to stabilize the trunk. A mechanical braking system is mounted beneath the seat and integrated to the pull phase of the rowing cycle to prevent lower extremities collapse. Two adjustable safety stops were installed on the rail and two springs installed on the seat to limit motion for knee joint protection against hyperextension and hyperflexion.

Fig.1. Modified indoor rowing machine

A humanoid model was designed based on the anthropometric data obtained from Winter (1990). The humanoid model developed in this work is based on human body whose height is 1.70m and weight is 65kg. Symmetrical property of the body segment is important to ensure that segments on either side of the humanoid are positioned symmetrically around the sagittal plane. The final stage of the development of the indoor rowing exercise model is to combine the humanoid model into the machine. It is important to ensure that the humanoid model is attached to the indoor rowing machine model at the right position. Since the movement of the humanoid model is symmetrical between left and right body, the trunk of the humanoid model has to be positioned in the middle of the seat. The complete model of the indoor rowing machine is shown in Fig.2.

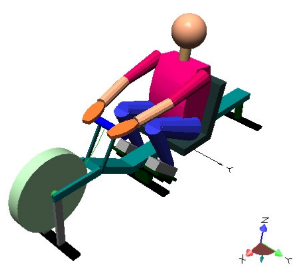

Fig.2. Indoor Rowing Exercise Model

2.2 *Physiological based Muscle Model.*

The physiological based muscle model for indoor rowing exercise was constructed based on the work by Riener and Fuhr (1998). The non-linear model describes the major properties of muscle and segmental dynamics of human during FES-assisted indoor rowing exercise. The muscle model also accounts for the impairment of the patient (paraplegic) to reflect the real patient behaviors for indoor rowing exercise.

Two groups of mono-articular muscles for knee extensor (quadriceps) and flexor (hamstrings) are developed. The muscle model developed is composed of three parts, namely muscle activation, muscle contraction and body segmental dynamics. The muscle activation model comprises four main components: non-linear recruitment characteristic, frequency characteristic, calcium dynamics and muscle fatigue (Fig.3).

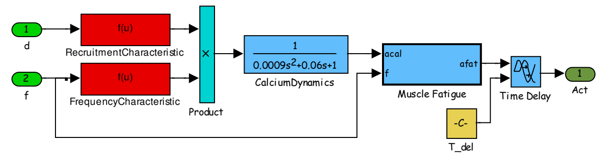

Fig.3 Muscle activation model

The muscle contraction accounts for the non-linear force-length property, f_{fl} and force-velocity property, f_{fv}, of the muscle and scales the muscle activation, act, by maximum isometric muscle force, F_{Max}, in order to obtain the absolute muscle force. The active joint moment for each muscle is then obtain from the product of moment arm and muscle force (Fig.4).

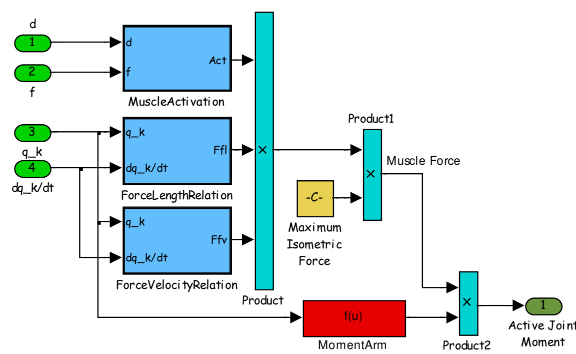

Fig.4 Muscle contraction model

The passive muscle properties are divided into two components: passive elastics, $M_{ela,j}$ and passive viscous joint moments, $M_{vis,j}$. The total joint moment is the combination of these moments.

The passive joint moments are given as:

$$\begin{aligned} M_{ela,A} &= \exp(2.0111 - 0.0833\varphi_A - 0.0090\varphi_K) \\ &\quad - \exp(-9.9250 + 0.2132\varphi_A) - 2.970 \end{aligned} \tag{1}$$

$$\begin{aligned} M_{ela,K} &= \exp(1.0372 + 0.0040\varphi_A - 0.0494\varphi_K - 0.0250\varphi_H) \\ &\quad - \exp(-1.1561 - 0.0020\varphi_A + 0.0254\varphi_K + 0.0030\varphi_H) \\ &\quad + \exp(2.5000 + 0.2500\varphi_K) + 1.0 \end{aligned} \tag{2}$$

$$\begin{aligned} M_{ela,H} &= \exp(2.1080 - 0.0160\varphi_K - 0.0195\varphi_H) \\ &\quad - \exp(-2.1784 + 0.070\varphi_K + 0.1349\varphi_H) - 15.24 \end{aligned} \tag{3}$$

$$M_{vis,j} = k_j \dot{\varphi}_j \tag{4}$$

The model of each of the muscle group developed in this work depends on the specific parameters of the muscle and independent parameters of the muscle derived by Riener and Fuhr (1998). The non-linear muscle model developed is then incorporated into the humanoid model described earlier as a complete model of paraplegic for indoor rowing exercise.

3. IMPLEMENTATION OF CONTROL STRATEGIES

The total joint moment generated by the muscle model to drive the rowing sequence depends on stimulated pulse width as the frequency is fixed to 33Hz. A specific control strategy is required to regulate the stimulated pulse width in order to obtain smooth rowing manoeuvre. In this study, four fuzzy logic controllers are designed to control knee extensor and flexor for both legs to perform smooth rowing manoeuvres. The rowing sequence is divided into 4 phases. These are Main Extension phase where quadriceps muscle is activated to drive the rowing backward, Resistance Extension phase where Hamstrings muscle is activated to slow down the rowing backward manoeuvre, Main Flexion where hamstrings muscle is activated for recovery phase and Resistance Flexion phase to slow down the backward rowing manoeuvre by activating the quadriceps muscle.

3.1 Design of Fuzzy Logic Controller.

There are 3 inputs selected for the controller. These are the error (difference between actual knee trajectory and reference knee trajectory), change of error and selection of rowing phase. The error and change of error are measured from the Visual Nastran indoor rowing exercise simulation model as the system outputs. The selection of rowing phase is used as the third input as to control the selection of muscle to be activated. The output is the stimulated pulse width. Five Gaussian (bell-shaped) type membership functions are used for each input, Error and Change of Error. Two membership functions for rowing phase input and five membership functions for output are used.

Tables 1 and 2 show the fuzzy rules for stimulated pulse width for quadriceps muscle when the rowing phase is (Ext) and (Flex) respectively. Tables 3 and 4 show the fuzzy rules for stimulated pulse width for hamstrings muscle when the rowing phase is (Ext) and (Flex) respectively.

Table 1 Fuzzy rules for Main Extension

E \ ΔE	NB	NS	Z	PS	PB
NB	**PB**	**PB**	**PB**	**PS**	**PS**
NS	**PB**	**PB**	**PS**	**PS**	**Z**
Z	**PB**	**PS**	**PS**	**Z**	**Z**
PS	**PS**	**PS**	**Z**	**Z**	**Z**
PB	**PS**	**Z**	**Z**	**Z**	**Z**

Table 2 Fuzzy rules for Resistance Extension

E \ ΔE	NB	NS	Z	PS	PB
NB	**Z**	**Z**	**Z**	**PS**	**PS**
NS	**Z**	**Z**	**PS**	**PS**	**PB**
Z	**Z**	**PS**	**PS**	**PB**	**PB**
PS	**PS**	**PS**	**PB**	**PB**	**PB**
PB	**PS**	**PB**	**PB**	**PB**	**PB**

Table 3 Fuzzy rules for Main Flexion

E \ ΔE	NB	NS	Z	PS	PB
NB	**Z**	**Z**	**PS**	**PS**	**PB**
NS	**Z**	**PS**	**PS**	**PB**	**PB**
Z	**PS**	**PS**	**PB**	**PB**	**PB**
PS	**PS**	**PB**	**PB**	**PB**	**PB**
PB	**PB**	**PB**	**PB**	**PB**	**PB**

Table 4 Fuzzy rules for Resistance Flexion

E \ ΔE	NB	NS	Z	PS	PB
NB	**PS**	**PS**	**PS**	**PS**	**Z**
NS	**PS**	**PS**	**PS**	**Z**	**Z**
Z	**PS**	**PS**	**Z**	**Z**	**Z**
PS	**PS**	**Z**	**Z**	**Z**	**Z**
PB	**Z**	**Z**	**Z**	**Z**	**Z**

The rules are typically fired as:

*If Error is **NB**, and Change of Error is **NB** and Selection is **Ext** then the Pulse Width is **PB**.*

*If Error is **PB**, and Change of Error is **NS** and Selection is **Flex** then the Pulse Width is **PS**.*

4. SIMULATION RESULTS

The control strategy was implemented in Matlab/Simulink with incorporation of indoor rowing exercise model in Visual Nastran to illustrate the effectiveness of the control method for FES-assisted indoor rowing exercise. The control objective is to regulate the level of stimulated pulse width for muscle stimulation to perform smooth rowing manoeuvre by following the reference trajectory. The reference knee and elbow trajectory for rowing sequence with upper body effort is shown in Fig. 5. Fig.6 shows the result of knee trajectory after several attempts of parameter tuning. It is noted that the FLC approach worked very well for the FES-assisted indoor rowing exercise. The knee trajectory followed the reference closely.

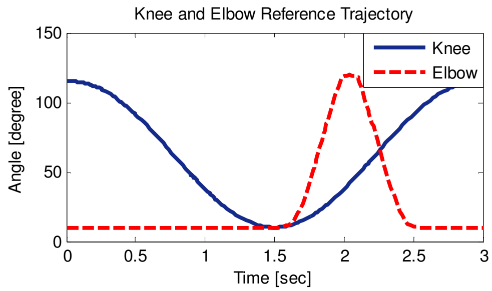

Fig.5. Reference Knee and Elbow trajectories

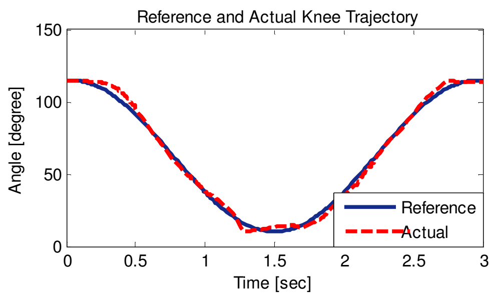

Fig.6. Reference and actual knee trajectories

Fig.7 shows the error between the reference trajectory and actual knee trajectory. The error is considered small for a complex physiological based muscle model. The maximum error was about 6.3% (7^0). Fig.8 shows the knee torque generated from the stimulated muscle extensor and flexor. The amounts of torque generated are in the range of -45.5Nm to 25Nm (negative values indicate the knee extensor), which are acceptable for paraplegics.

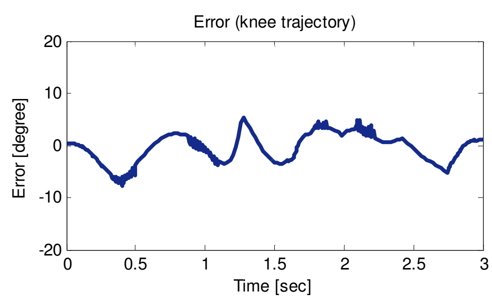

Fig.7. Error of knee trajectory

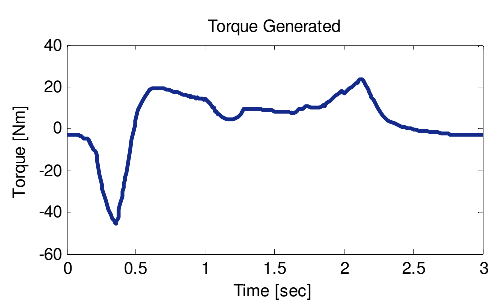

Fig.8. Torque generated

Fig.9 shows the stimulated pulse width generated from fuzzy logic controller output. The quadriceps was stimulated for short period of time to drive the backward rowing manoeuvre (main extension phase) but the hamstrings muscle was stimulated twice and over a longer time to perform the resistance drive phase and main flexion phase.

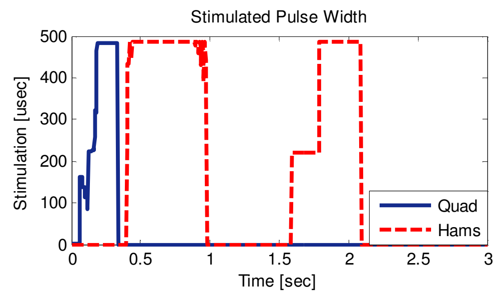

Fig.9. Stimulated pulse width

5. CONCLUSION

A fuzzy logic controller has been successfully implemented to regulate the level of stimulation pulse width used to stimulate the knee extensor and flexor muscle for FES-assisted indoor rowing exercise. Based on the control strategy developed, a smooth rowing manoeuvre has been achieved. A physiological based artificially activated muscle model generates adequate amounts of torque to drive the knee extensor and flexor through out the rowing manoeuvre. It is noted that the track, where the seat slides, is positioned horizontally (normally 10^0 inclined). This leads to higher stimulation of hamstrings muscle (knee flexor) compared to quadriceps muscle (knee extensor) due to hamstrings as a weaker muscle group. Future work will investigate different degrees of inclination of track to achieve optimal stimulated pulse width for smooth rowing manoeuvre with consideration of muscle fatigue and upper body effort.

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