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Cycle to Cycle Control in FES-Assisted Elliptical Stepping Exercise

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Abstract— **The development of FES-assisted exercise system is a challenging task due to the dynamic behavior of the muscular skeletal system. This paper presents the design of the cycle to cycle control technique based on the fuzzy logic control (FLC) algorithm for FES-assisted elliptical stepping exercise. The control aims to produce an appropriate FES stimulation signal for quadriceps muscle that actuates the knee joint movement during the exercise. The design is done through a computer simulation that involves the modeling of the exercise system and development of the controller. The performance of the FLC based cycle to cycle control technique is evaluated based on the response in terms of the exercise movement. The produced FES stimulation signal for activating the quadriceps muscle is also recorded and analyzed. Based on the analysis, the cycle to cycle control technique has shown a promising performance in controlling the FES-assisted elliptical stepping exercise.**

Keywords— ***Elliptical stepping exercise; fuzzy logic control (FLC); functional electrical stimulation (FES); cycle to cycle control***

I. INTRODUCTION

Functional Electrical Stimulation (FES) is a tool used in the rehabilitation of paralyzed muscle due to neurological disorder such as stroke and SCI. The control of the FES for activating the paralyzed muscle has evolved in line with the evolution of technology since the implementation for assisting foot drop by Liberson [1] in 1964. The FES control technique is addressed to many different applications whether for assisting the free-moving limb or with the use of exercise ergometer, orthosis, robotic limb and etc. In the application with the exercise ergometer, methods such as treadmill, cycling, rowing and stepping can be categorised as popular techniques of exercise. The design of control techniques is subjected to the nature of the movement of the exercise ergometer, the way the exercise is performed, the number of muscle group to be stimulated, etc.

The control techniques that implement methods such as the Proportional Integral Derivative (PID) control, fuzzy logic control (FLC), adaptive neuro-fuzzy and sliding mode control (SMC) are regarded as methods adopted to improve the performance of exercise with FES. This is especially true for automated FES-assisted exercise. The aims are mainly to reduce the occurrence of early muscle fatigue and hence allow the patients to do the exercise in longer duration. Longer exercise duration causes more muscle activity that encourages function regaining. This indicates that the control of FES is one of the important factors that contribute toward the success of any FES-assisted exercise for rehabilitation.

To achieve the aims of control in FES-assisted exercise is not a simple task since the design must deal with the dynamic response of the muscle. Reiner et al. [2] stated that real-time model applications within the neuroprosthesis (NP) controller are difficult or even impossible to realize with too complex models. Thus, the use of the control technique with fixed algorithm may not give much tolerance to cater for the dynamic response of the muscle.

Among the many control algorithms, FLC has an advantage in terms of flexible architecture [3] and simple algorithm [3,4]. The use of FLC has been proven to show a good performance in the implementation, both on the simulation basis or real plant basis. The best selection of control algorithm may not be fully effective without the best technique of implementation. The combination between the control algorithm and best technique of implementation is an important criterion to ensure the success of the control.

Cycle to cycle control is one of the techniques that can be implemented with appropriate control algorithm to achieve the control objective in FES-assisted exercise. This especially applies to the exercise that imposes repeating movements. In the cycle to cycle control, the FES stimulation signal has a fixed shape and changes will only happen once the new cycle starts. This is different from continuous control where the FES stimulation signal continuously changes throughout the exercise.

Ibrahim et al. [5] mentioned that the cycle to cycle control delivers FES in the form of open loop control in each cycle without the reference trajectory but is still closed-loop control. Chen [6] mentioned that a proper design of stimulation signal ensures smooth cycling without abruptly changing the cycling velocity, either a halting or jerking movement. Reported in [5][7], the control input of the cycle to cycle control is based on the previous cycle maximum point achievement. Thus, in the cycle to cycle control, much proper muscle force should be obtained due to the fact that constant amount of FES is applied at each stimulation cycle.

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In this work, FLC based cycle to cycle control is proposed for FES-assisted elliptical stepping exercise. This technique will be referred as FLC-C2C throughout this paper. The elliptical stepping exercise is a pedaling type of exercise that produces an elliptical shape of foot movement. Since the elliptical stepping exercise repeats the same movement in every cycle, the cycle to cycle control is suitable to be implemented. The study will compare the performance between the FLC-C2C with the previously implemented FLC based continuous control. The FLC based continuous control will be referred as FLC-C throughout this paper.

II. METHODOLOGY

The study is done in the simulation basis. A simulation model is developed to represent the real FES-assisted elliptical stepping exercise. The model consists of a humanoid model with body height of 170cm and body mass of 75kg. It also consists of an elliptical stepping ergometer model and wheelchair model that represent the dimension and features of the actual ergometer that is available in the Postgraduate Research Laboratory at the Faculty of Electrical Engineering, UiTM Pulau Pinang. The other models are quadriceps muscle model and the controller model.

A. Elliptical Stepping Exercise Model

The elliptical stepping exercise is a seated type of exercise. The model design has been detailed out in the author's two previous works [8-9]. The elliptical stepping exercise model is shown in Fig. 1. It is also linked with the quadriceps muscle model that was developed based on the model proposed by Reiner & Fuhr [10]. The detail of quadriceps muscle model development can be referred from the author's previous work [11]. The quadriceps muscle model consists of two set values as an input namely the stimulation pulse width and stimulation frequency. The stimulation pulse width ranges from 0-500*u*s, while the stimulation frequency is fixed at 30Hz. Thus, the FES stimulation signal is determined by the variation of the stimulation pulse width. The model is set to have movement according to the amount of joint torque that is produced at the knee joint of the humanoid model. This is achieved by equipping the knee mechanism with a revolute motor. The revolute motor input is linked to the output of the quadriceps muscle model.

The movement of the elliptical stepping exercise is shown in Fig. 2. At the elliptical stepping ergometer, the humanoid foot is secured at the stepping arm and linked with the flywheel via the crank arm. Thus, the crank arm that is connected to the center of the flywheel will have cyclical shape movement, while the humanoid foot will have elliptical shaped movement. For control purpose, the movement position that is used as feedback information is based on the position of the crank arm or flywheel. The position labeled in Fig. 2 is the point where the crank arm and flywheel are at starting position (0˚) where the end position of the movement cycle is also at the same point (360˚). Since the model is developed to have the flywheel rotation position at 0˚ when the left crank arm is at 0˚, it is easy to use the flywheel rotation position as the reference.

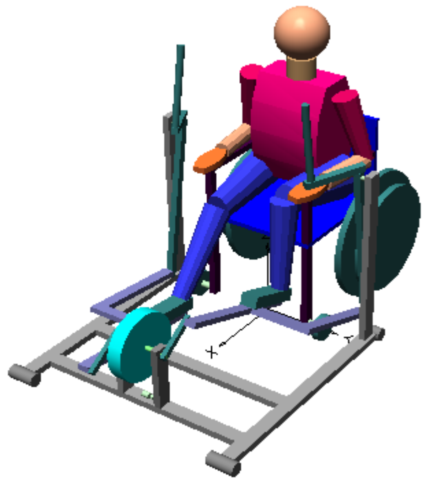


Fig. 1. Elliptical stepping exercise model

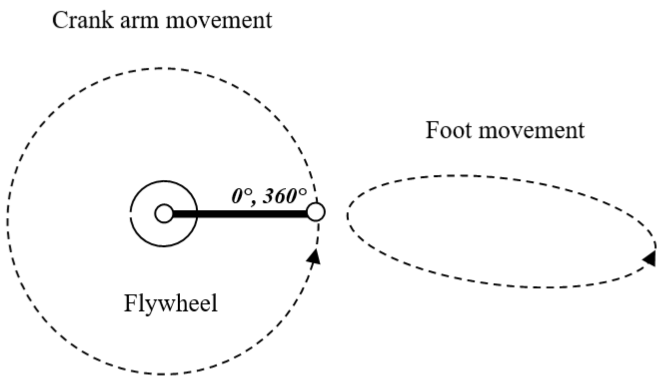


Fig. 2. Shape of movement for foot and crank arm.

B. Fuzzy Logic Control (FLC) and Particle Swarm Optimization (PSO)

Fuzzy logic control (FLC) used in this work is set to have two control inputs and one control output. As the right leg depicts the non-paretic leg, the same configuration of the FLC and optimized scaling factor as obtained in [12] is used in this work. However, for the left leg that is paretic, the FLC is restructured to suit with the proposed FLC-C2C. The first input is the cadence error of the previous cycle at a position before the new cycle starts. Meanwhile, the second input is the time per cycle error of the previous cycle. The output is the control signal that represents the FES stimulation signal. Triangular-shaped membership function is used for the inputs and output mapping. Stated in [6], the triangular-shaped membership function yields less steady state error compared to other functions.

The membership functions for FLC-C2C control are shown in Fig. 3. The inputs and output were broken into 7 fuzzy sets in order to have better refining of the fuzzy input and output mapping. The two inputs having the same type of fuzzy set cover from negative (-ve) to positive (+ve) input value and they are Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM) and Positive Big (PB). The fuzzy set for output covers the positive value from very small (VS), Medium Small (MS), Small (SM), Medium (ME), Big (BG), Medium Big (MB) and Very Big (VB). Thus, the control signal that will be produced by the FLC-C2C will have a range from very small to very big.

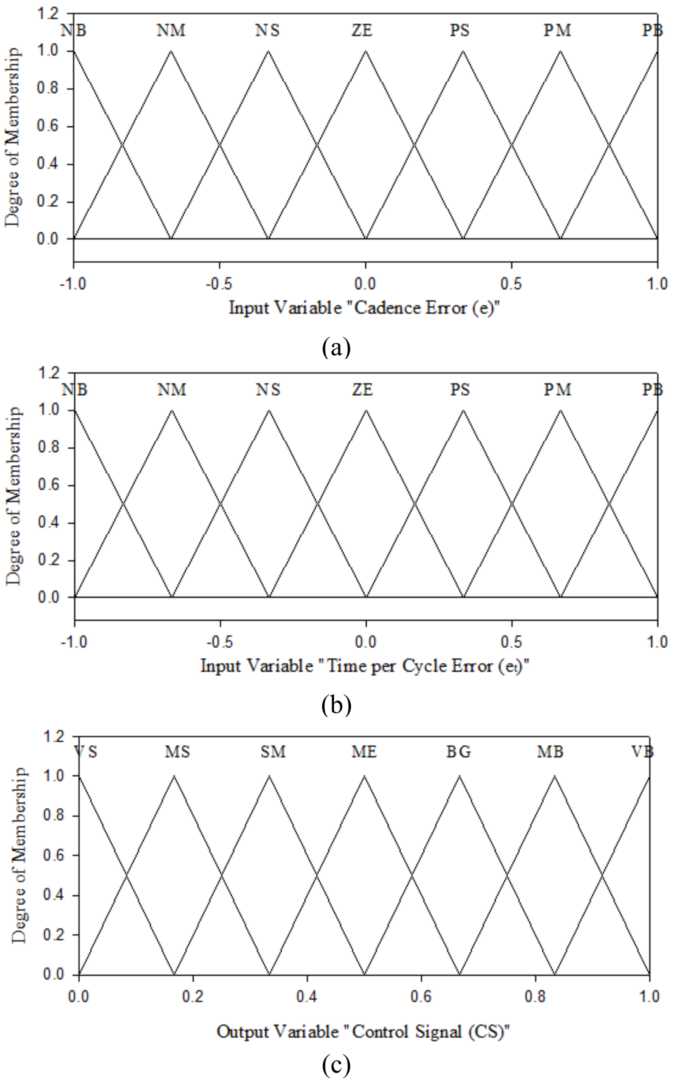


Fig. 3. FLC membership function (a) input 1: cadence error (b) input 2: time per cycle error (c) output: control signal

The FLC control action is mapped into the fuzzy rules matrix and is shown in Fig. 4. To map the input and output into the fuzzy environment, scaling factors are used at the inputs and output of the FLC. Since it is difficult to determine the suitable value of the scaling factors, an optimization technique is used. The particle swarm optimization (PSO) technique is used to optimize the parameters of the FLC-C2C control technique. The PSO structure is based on Kennedy and Eberhart (1995) [13], Shi and Eberhart (1998) [14] and Ratnaweera et al. (2004) [15].

$e \backslash e_t$	NM	NM	NS	ZE	PS	PM	PB
NB	ME	SM	SM	MS	MS	VS	VS
NM	BG	ME	SM	SM	MS	MS	VS
NS	BG	BG	ME	SM	SM	MS	MS
ZE	MB	BG	BG	ME	SM	SM	MS
PS	MB	MB	BG	BG	ME	SM	SM
PM	VB	MB	MB	BG	BG	ME	SM
PB	VB	VB	MB	MB	BG	BG	ME

Fig. 4. FLC rules

C. *Cycle to Cycle Control*

The cycle to cycle control is a technique that adapts both open loop and closed loop concepts in it. Open loop is due to the controller not continuously receiving update signals from the system output. Closed loop is due to the controller still relying on the feedback signal from the system output, but in terms of the accumulated value. The structure of the cycle to cycle control is shown in Fig. 5. Two control inputs are used for the cycle to cycle control and both are based on the cadence of the elliptical stepping. The measurement of cadence is a possible way to observe the muscle performance since the torque-cadence relationship is proportional. In this work, torque (knee joint torque) is produced by the stimulation of the quadriceps muscle. Thus, changes of cadence at the same FES stimulation signal may indicate the changes of the muscle performance.

The first input is the cadence error of the previous cycle at the position before the new cycle starts. When the new movement cycle starts, this value is set to be constant and to become the input to the FLC. The second input is the time per cycle error of the previous cycle. The time is compared with the desired time and the error is set as constant and it is to become the input to the FLC. The flywheel rotation position in the range between 340°→360°/0°→120° is set as the range of starting and end point of the stimulation for every cycle. This is in order to consider the effect of time delay between the stimulation and muscle response. Other than that, this is also to avoid movement overshoot due to the high knee joint torque that is produced by the constant value of the FES stimulation signal.

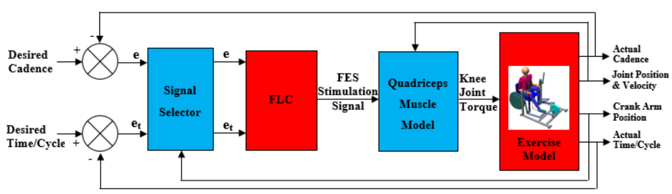


Fig. 5. Cycle to cycle control structure

III. RESULT AND DISCUSSION

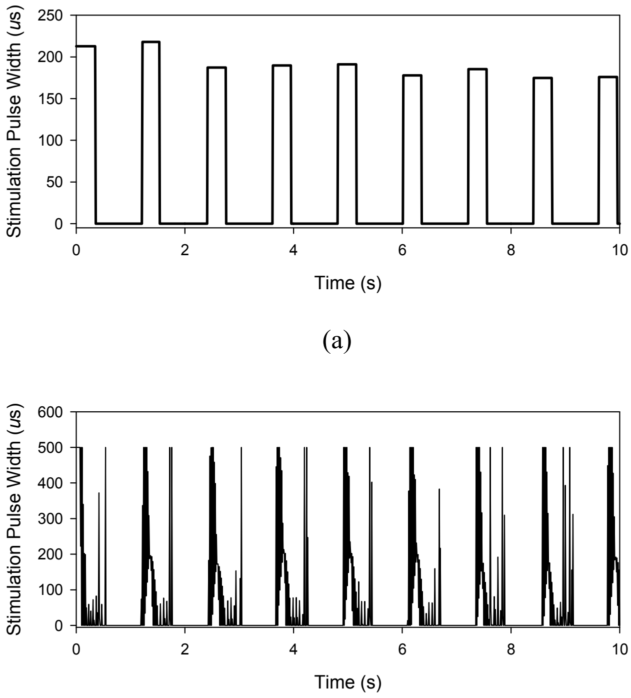
The performance of the FES-assisted elliptical stepping exercise is evaluated through a comparative assessment of the performance between the FLC-C2C and FLC-C control technique. The values of the FLC scaling factors for both FLC-C2C and FLC-C control technique that were obtained through the PSO optimization are shown in TABLE I. Furthermore, an adjustment is done to determine the fixed starting and end position of the stimulation. This is done by the trial and error method. Once all the parameters are finalized, the elliptical stepping exercise model is test-run for 30 sec to observe the performance.

TABLE I. OPTIMIZED SCALING FACTOR

Parameter		FLC-C	FLC-C2C
Scaling Factor (Left FLC)	e	0.02791	0.04012
	Δe	0.00356	2.33840
	PW	674.67	425.63
Scaling Factor (Right FLC)	e	0.0313	0.0313
	Δe	0.00177	0.00177
	PW	77.06	77.06

Fig. 6 shows the comparison between the FLC-C2C and FLC-C in terms of the produced FES stimulation signal. As can be seen, the FES stimulation signal of the FLC-C2C has a constant value at every cycle and the variation between one cycle to another is also in small range. The FLC-C2C estimated the average FES stimulation signal and drove one cycle of movement with a constant FES stimulation signal. By delivering a constant FES stimulation signal, the sudden increase and decrease of the muscle stimulation can be avoided. This will improve the way the muscle is being activated in each cycle of movement. Meanwhile for the FLC-C, a random FES stimulation signal is produced at every cycle and the value sometimes fluctuates to the maximum. This normally happens mostly at the starting of each cycle where the controller is trying to compensate for the decreasing cadence. However, this may cause overshoot to the movement.

Fig. 7 shows the comparison between the FLC-C2C and FLC-C in terms of maximum positive cadence error in every cycle. This performance indicates the ability of the controller to compensate for the decreasing cadence in order to maintain the cadence at a desired level. As can be seen, the positive cadence error of the FLC-C2C is about half of the FLC-C. Excluding the starting cycle, the average maximum positive cadence error for both control techniques are 5.06 RPM and 10.55 RPM respectively. There are 25 completed cycles in 30 sec for both techniques. It shows that these two techniques are capable of ensuring that the desired 50 RPM cadence is achieved within the 30 sec, but in terms of the smoothness of the exercise movement, the FLC-C2C shows better performance due to the low variation of the cadence error.



(b)

Fig. 6. FES stimulation signal (10 sec sampling), (a) FLC-C2C (b) FLC-C

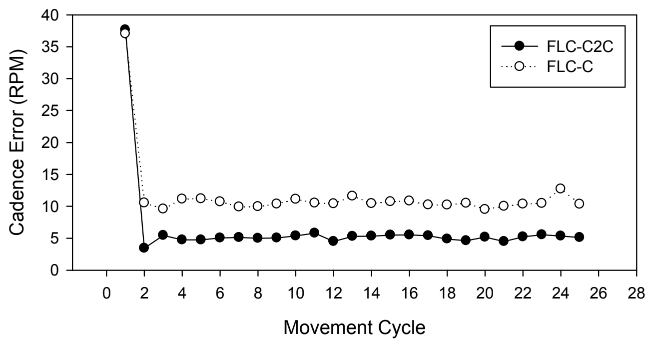


Fig. 7. FLC-C2C and FLC-C cadence error comparison

IV. CONCLUSION

This paper presented the implementation of the FLC based cycle to cycle control for the FES-assisted elliptical stepping exercise. The cycle to cycle control is capable of providing appropriate control of the FES stimulation signal during exercise with the FES. The technique ensures that the muscle being stimulated receives just enough stimulation intensity to complete the desired movement. This is measured in this work by observing the smoothness of the movement. Achieving constant cadence at each cycle is impossible due to the influence of the exercise mechanism and both leg response (paretic and non-paretic); however with a good control technique, the variation of the cadence error at each cycle can be reduced. Based on the analysis that has been done, the proposed FLC-based cycle to cycle control has shown a promising result in achieving the desired control performance.

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