

Fuzzy Logic based Cycle-to-Cycle Control of FES-induced Swinging Motion

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Abstract— FES induced movement control is a significantly challenging area due to complexity and non-linearity of musculo-skeletal system. The goal of this study is to design a cycle-to-cycle control of FES-induced swinging motion. In this approach only the quadriceps muscle is stimulated by controlling the amount of stimulation pulselwidth. This time dependent behaviour is successfully compensated for using a cycle-to cycle fuzzy controller, which computes the amount of knee extension stimulation on the basis of the achieved flexion angle in previous cycles. The capability of fuzzy control in automatic generation of stimulation burst duration is assessed in computer simulations using a musculo-skeletal model. This paper presents the development of a fuzzy logic control scheme based on discrete-time cycle to cycle control strategies without predefined trajectory. The results show the effectiveness of the approach in controlling FES-induced swinging motion

Keywords- Functional electrical stimulation, fuzzy logic, genetic algorithm, swinging motion, quadriceps, paraplegic.

I. INTRODUCTION

Many researchers have developed electrically stimulated muscle control ranging in levels of sophistication from simple to complex. Primarily due to the complexity of the system (nonlinearities, time-variation) practical FES systems are predominantly open-loop where the controller receives no information about the actual state of the system [1]. In its basic form, these systems require continuous user input. Practical success of this open-loop control strategy is still, however, seriously limited due to the fixed nature of the associated parameters.

Accurate control of FES-induced movement can be ensured with a suitable closed-loop adaptive control mechanism. Such approach has several advantages over open-loop schemes, including better tracking performance and smaller sensitivity to modeling errors, parameter variations, and external disturbances. Although conventional PID control is still the most widely adopted method in industry for various control applications due to its simple structure, ease of design, and low implementation cost, it might not perform satisfactorily if the system to be controlled is of highly nonlinear and/or uncertain nature [2]. Classical closed-loop control algorithms have failed to provide satisfactory performance and are not able to guarantee stability, a desired property of the controlled system [3].

Jezernik et al. (2004) used sliding mode FES control to regulate knee joint angle. The controller was tested on six neurologically

intact subjects and two untrained paraplegic subjects. Good tracking of a desired knee joint trajectory was achieved, but this could only be applied to mathematical model based plant. The overall model of the plant being considered is a multi-input-multi-output (MIMO) nonlinear model consisting of nonlinear lumped parameters comprising passive joint viscoelasticity and active joint properties and segmental dynamics. On the other hand, fuzzy logic control (FLC) has long been known for its ability to handle nonlinearities and uncertainties without the need for mathematical model of the plant. Thus FLC is the preferred option in the current work.

In controlling cyclical movement, one can try to follow pre-set joint angle trajectories. In the swing phase of gait, following exact trajectories is unimportant and inefficient, leading to fatigue due to the large forces that must be exerted to precisely control the high inertia body segments (Crago et al., 1996). Therefore, the cycle-to-cycle control method is expected to be an alternative to the trajectory based closed-loop FES control. The cycle-to-cycle control delivers the electrical stimulation in the form of the open-loop control in each cycle without reference trajectory but it is still closed-loop control. In this control strategy, movement parameters at the end of each cycle were compared to the desired set point, and the stimulation for the next cycle was adjusted on the basis of the error in the preceding cycle.

This paper presents the development of strategies for swinging motion control by controlling the amount of stimulation pulselwidth to the quadriceps muscle of the knee joints. Capability of the controller to control knee joint movements is assessed in computer simulations using a musculoskeletal knee joint model. The knee joint model developed in Matlab/Simulink, as described in [4], is used to develop an FLC-based cycle-to-cycle control strategy for the knee joint movement. The FLC output is the controlled FES stimulation pulselwidth signal which stimulates the knee extensors providing torque to the knee joint. The swinging movement is performed by only controlling stimulation pulselwidth to the knee extensors to extent the knee and then the knee is left freely to flex in the flexion period.

II. MATERIALS AND METHOD

The role of simulation was to design, test, and optimize the control strategies, thus reducing time-consuming trial and error adjustments during human experiments.

A. Model of Knee Joint

The shank-quadriceps dynamics are modelled as the interconnection of passive and active properties of muscle model and the segmental dynamics. The total knee-joint moment is given by (Ferrarin, 2000):

$$M_i = M_a + M_g + M_s + M_d \quad (1)$$

where M_a refers to an active knee joint moment produced by electrical stimulation, M_s is the knee joint elastic moment and M_d is the viscous moment representing the passive behaviour of the knee joint. In this research the $M_i - M_g$ is represented by equation of motion for dynamic model of the lower limb while M_a and $M_s + M_d$ are represented by a fuzzy model as active properties of quadriceps muscle and passive viscoelasticity respectively. A block diagram of the knee joint model consisting of active properties, passive viscoelasticity and equations of motion of the lower limb is shown in Fig. 1. The active joint moment is added with the passive joint moment as an input (torque) to the lower limb model and this will produce the knee angle as the output.

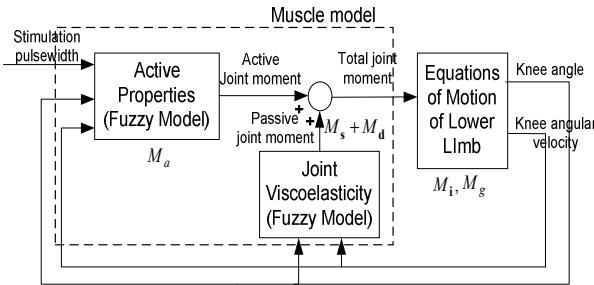


Figure 1. Schematic representation of the knee joint model

A schematic diagram of the lower limb model is shown in Fig. 2, where q_2 = shank length, r_1 = position of centre of mass (COM) along the shank, r_2 = position of COM along the foot, θ_1 = knee angle and θ_2 = ankle angle. The leg movements were described as a double pendulum with constant ankle angle. Hence, the motion dynamics can be represented in a simpler form. The gravitational (M_g) moment is represented by:

$$M_g = m_1 g \cos \theta_1 r_1 + m_2 g \cos \theta_1 q_2 \quad (2)$$

The inertial (M_i) moment is represented by mathematical model of the lower limb based on Kane's equations as follows:

$$M_i = -m_2 q_2 \dot{\theta}_1^2 r_2 - I_1 \ddot{\theta}_1 - m_1 r_1^2 \ddot{\theta}_1 - m_2 q_2^2 \ddot{\theta}_1 \quad (3)$$

where, m_1 = shank mass, m_2 = foot mass, I_1 = moment of inertia about COM, $\dot{\theta}_1$ = knee velocity, $\ddot{\theta}_1$ = knee acceleration, g = acceleration due to gravity.

The anthropometric inertia parameters of the subject's lower limb were optimised based on passive pendulum test as described in (Ibrahim et al., 2010), and these are shown in Table 1.

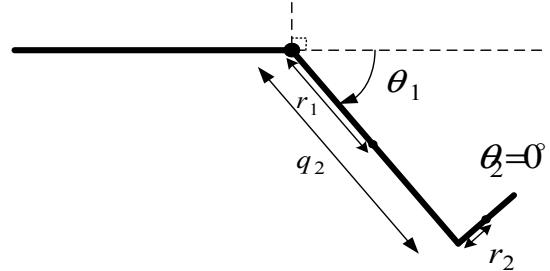


Figure 2. Lower limb model

TABLE 1. ANTHROPOMETRIC DATA OF SUBJECT

Parameter	Value
Shank length (m)	0.43
Foot length (m)	0.068
Position of COM of shank (m)	0.22
Position of COM of foot (m)	0.035
Foot Mass (kg)	0.95
Shank Mass (kg)	3.5
Moment of Inertia (Nm ²)	0.36

The knee joint model input is the stimulation pulselength as would be delivered by an electrical stimulator in reality. Thus a complete model of knee joint developed is utilized as platform for simulation of the system and development of control approaches.

B. Controller Development

FLC is the fastest growing soft computing tool in medicine and biomedical engineering [6]. It is being used successfully in an increasing number of application areas in the control community. FLCs are rule-based systems that use fuzzy linguistic variables to model human rule-of-thumb approaches to problem solving, and thus overcoming the limitations that classical expert systems may face because of their inflexible representation of human decision making. The major strength of fuzzy control also lies in the way a nonlinear output mapping of a number of inputs can be specified easily using fuzzy linguistic variables and fuzzy rules [7]. The control signal is computed by rule evaluation called fuzzy inference instead of by mathematical equations.

The cycle-to-cycle control approach retains this basic mechanism of movement generation through stimulus burst and comes into action when the movement is repetitive or cyclical, through automatic adjustment of the burst parameters to maintain the desired target orientation at each cycle [8]. Cycle-to-cycle control is a method for using feedback to improve product quality for processes that are

inaccessible within a single processing cycle. In the discrete-time cycle-to-cycle control, muscle is stimulated by single burst of controlled stimulation pulsewidth for each cycle to induce joint movement reaching the target extension knee angle [9]. Therefore, the method is different from the traditional closed-loop control such as tracking control of desired angle trajectory.

The outline of the discrete-time fuzzy control based cycle-to-cycle control is shown in Fig.3. The controlled maximum joint angle of the previous cycle is delivered as feedback signal. Error is defined as difference between the target and measured joint angle. The controller will regulate the duration of stimulation pulsewidth based on the error; if the error is high then the duration of the next stimulation pulsewidth will be wider than previous cycle, and if the error is low then the duration of the next stimulation pulsewidth will be shorter. The duration of stimulation pulsewidth will change according to the error of previous cycle.

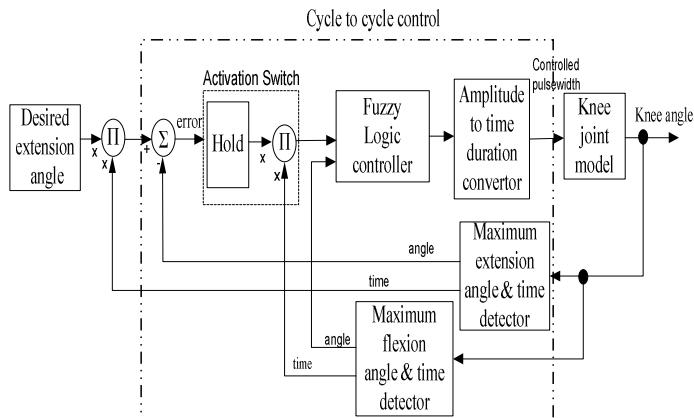


Figure 3. Discrete-time FLC based cycle to cycle control

1) Maximum flexion and extension detector

The maximum flexion time detector will detect the time the angle reaches the peak of knee flexion for each cycle. While, the maximum extension signal and time detector will detect the peak angle of knee extension and the time the knee angle reaches this point for each cycle. The extension and flexion stages of the knee angle are shown in Fig. 4.

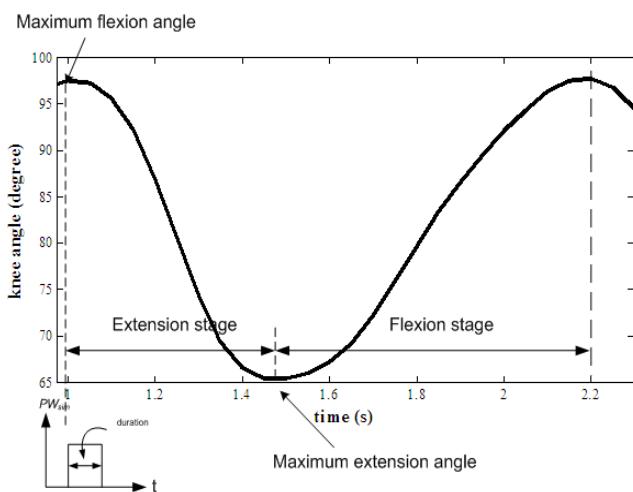


Figure 4. Extension and flexion stages

2) Activation switch

Activation switch consists of hold and multiplier block to be active only when the knee angle reaches maximum flexion. The activation switch will hold the error signal and produce the output whenever it receives a signal from the maximum flexion time detector.

3) Amplitude to time duration convertor

Amplitude to time duration converter is linearly converting the controlled signal (amplitude) from controller to time duration using signal comparator and shifting technique as shown in Figure 6.3. In this technique, first the controlled signal is compared with specific constant values for low to high in the parallel structure. Each comparator compares the controlled signal with the specific constant, if the controlled signal is greater than or equal to the specific constant then a single pulse will pass through the comparator. The first comparator compares the control signal with zero, if there is any signal from controller then the output will be a pulse with 0.05s width. The second comparator compares the control signal with specific constant and shift 0.05s and the next comparator compares and shifts by a further 0.05s. Then the resultant pulse duration for each cycle is obtained by summing up the total pulses passed through the comparators and amplifying the signal with 220 μ s. The higher the controlled signal the more gates can be passed through and the wider the duration of pulse. Therefore the output of this converter is a single burst of controlled stimulation pulse duration with constant amplitude (220 μ s) for each cycle.

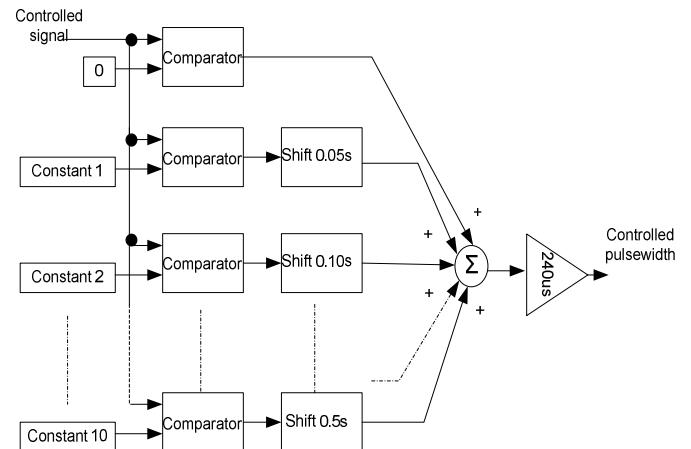


Figure 5. Signal comparator and shifting technique

4) Controller Objectives

The FLC-based cycle-to-cycle control was designed to achieve the following objectives:

- To reach full knee extension
- To reach target extension angle thus maintain a steady swinging motion.

4) Design of Discrete-time Fuzzy Controller

Measured output of the controlled musculoskeletal system of the previous cycle is delivered as feedback signal. Proper value of signal is determined and regulated automatically by a Sugeno-type fuzzy controller using control rules as shown in Table 2. Input membership function is expressed as triangle fuzzy sets. Output membership function is expressed as fuzzy singletons. Input of fuzzy controller is aggregated by fuzzy inference using fuzzy rules to produce control action.

The fuzzy rules base directs control action based on error and flexion angle. The error will be higher when the muscle fatigues, in which case the response to a stimulation burst will change. To compensate for this changing system response, the stimulation burst time has to be increased such that shank can reach the desired angle in every cycle. The flexion angle was taken into account to rule out the disturbance. Combination of the information about error and knowledge about flexion angle will be necessary for controller to give an appropriate stimulation pulselwidth.

TABLE 2: FUZZY RULES

		Flexion angle					
		Very High	High	Normal	Low	Very Low	Extremely Low
Error	Neg	Low	Low	Low	Low	Zero	Zero
	Zero	Low	Low	Low	Low	Zero	Zero
	Pos	Low	Normal	Normal	Very Low	Very Low	Zero

III. RESULTS AND DISCUSSION

A complete set of non-linear dynamic equations of the knee joint model comprising the passive properties and active properties have been used in the simulations for purposes of controller development. Computer simulations are performed to assess the performance of the designed discrete-time cycle-to-cycle control approach in generating stimulation burst durations for the desired extension angle. The simulation was carried out within the Matlab/Simulink environment. FES induced swinging motion was controlled using fuzzy control based cycle-to-cycle control to achieve the target extension angle and thus maintain a steady swing of the limb.

This discrete-time fuzzy logic cycle to cycle control technique emphasizes with a view to overcome some drawbacks of the trajectory based closed-loop FES control such as poor tracking, oscillating response and inability to reach full knee extension angle [10]. The ability of this control approach to realize the target joint orientation has been assessed in simulation as follows:

1.1 Full knee extension angle

The test was initiated with stimulation pulse of $240\mu\text{s}$ amplitude with 0.3s burst duration for the first cycle of swing in gait before activating the controller. FES induced swinging motion was controlled using fuzzy controller to reach full extension angle. The full extension angle that can be achieved by paraplegic was defined as 10° . The computer simulation test was performed with stimulation course of 50 cycles. The first 5 cycles of the controlled swinging leg test of the full extension knee angle are shown in Figure 6. As can be seen, using FLC-based cycle-to-cycle control approach the first objective was achieved; to reach the full knee extension. The knee reached full extension at 3rd cycle and was able to maintain the swinging motion without any predefined trajectory.

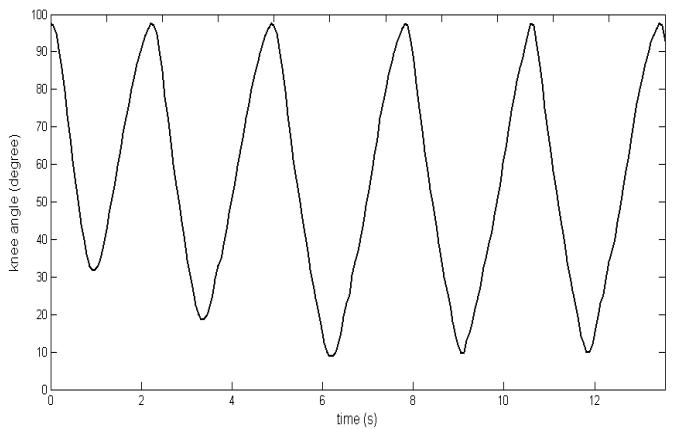


Figure 6. Controlled swinging leg for desired angle at 10° (full extension)

1.2 Target extension angle and thus maintain a steady swing

The test is to achieve the target extension angle and thus maintain a steady swing of the shank. The desired extension knee angle was set to be at 65° as considered in [11]. The test was initiated with stimulation pulse of $220\mu\text{s}$ amplitude with 0.25s burst duration for the first cycle before activating the controller. In the each test computer simulation was performed with stimulation course of 50 cycles. The first 10 cycles of the controlled swinging leg test of the knee joint at 65° is shown in Figure 7. As can be seen the cycle-to-cycle control approach can achieve the target extension angle at 3^{rd} and thus maintain a steady swing of the shank. It is noted that the performance of the controller was quite good and acceptable.

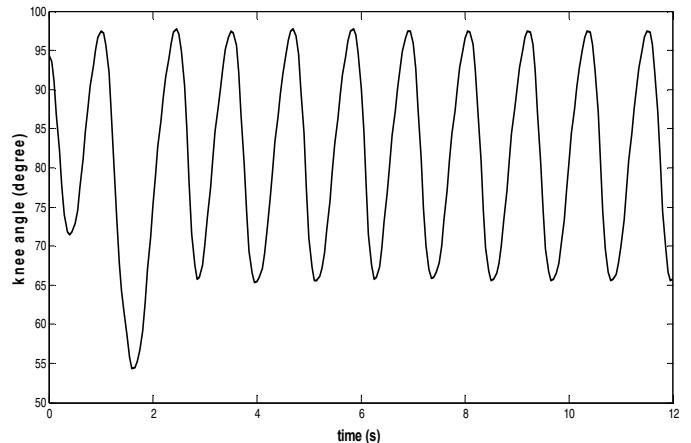


Figure 7. Controlled swinging leg

The muscle model was controlled by changing the pulse width; however the amplitude and the frequency of the stimulation pulses were constant. The cycle-to-cycle control approach, unlike closed-loop tracking control, can produce full knee extension and does not impose any predefined trajectory. While the trajectory based closed-loop control for knee joint angle of paraplegic has been criticized for poor tracking and oscillatory response and even its inability to reach full knee extension angle [10].

IV. CONCLUSION

FES induced movement control is a difficult task due to the highly time-varying and nonlinear nature of the muscle and segmental dynamics. The merit of a musculoskeletal model of knee joint is to serve for control development. In this study, a new closed-loop control approach using fuzzy logic based cycle-to-cycle control for FES-induced motion control has been proposed. This control technique also emphasizes to overcome some drawbacks of the trajectory based closed-loop FES control. The objectives of this controller have been set to achieve full knee extension angle, to reach target extension angle thus maintain a steady swinging motion. The performance of the controller to achieve these objectives has been assessed through simulation study. Cycle-to-cycle control has been shown to compensate for non-linearity and time-variance of response of electrically stimulated musculoskeletal system. The developed controller may be suitable not only for swinging but also for other FES control applications involving movement of cyclical nature.

REFERENCES

- [1] P.E. Crago, N. Lan, P. H. Veltink, J.J. Abbas and C.Kantor, "New control strategies for neuroprosthetic systems," Journal Rehabilitation Res Device, vol. 33, pp. 158-172, 1996.
- [2] M.S.Huq, "Analysis and control of hybrid orthosis in therapeutic treadmill locomotion for paraplegia," PhD Thesis, The University of Sheffield, Sheffield, UK, 2009.
- [3] S. Jezernik, R.G. Wasink, and T. Keller, "Sliding mode closed-loop control of FES: controlling the shank movement," IEEE Transaction Biomedical Engineering , pp. 263-272, 2004.
- [4] B.S. K. K. Ibrahim, M.O. Tokhi M.S. Huq, and S.C. Gharoomi, "An Approach for Dynamic Characterisation of Passive Viscoelasticity and Estimation of Anthropometric Inertia Parameters of Paraplegic Knee Joint," unpublished.
- [5] M. Ferrarin, and A. Pedotti, "The relationship between electrical stimulus and joint torque: a dynamic model," IEEE Transactions on Rehabilitation Engineering, vol. 8 , pp. 342-352, 2000.
- [6] H.N. Teodorescu, A. Kandel, L.C. Jain, "Fuzzy and Neuro-Fuzzy Systems in Medicine," CRC Press LLC, Boca Raton, Florida. 1999.
- [7] T.C. Chin, and X. M. Qi, "Genetic Algorithms for learning the rule base of fuzzy logic controller" Fuzzy Sets and Systems. vol. 97, 1998.
- [8] H. M. Franken, P. H. Veltink, R.Tijmans , H. Nijmeijer, , and H. B. K. Boom, "Identification of passive knee joint and shank dynamics in paraplegics using quadriceps stimulation," IEEE Transactions on Rehabilitation Engineering, vol. 1, pp. 154-164.1993.
- [9] A. Arifin, T. Watanabe, and N. Hashimiya, "A Test of fuzzy controller for cycle-cycle control of FES-induced hemiplegics gait: Computer simulation in single-joint control," Proc. 36th Control of Japanese Soc.& Med. & Bid. Eng., Tohoku Chapter, pp.30, 2002.
- [10] M.S. Hatwell, B.J. Oderkerk, C.A. Sacher, and G.F. Inbar, "The development of a model reference adaptive controller to control the knee joint of paraplegics," IEEE Transactions on Automatic Control, vol. 36, pp. 683–691, 1991.
- [11] T.D. Fahey, M. Harvey, R. Schroeder, and F. Ferguson,"Influence of sex differences and knee joint position on electrical stimulation-modulated strength increases," Medicine Science Sports Exercise, vol. 17, pp. 144-147, 1985.