Proceedings Paper:
Hussain, Zakaria, Bin Zaidan, Martha Arbayani, Tokhi, M.O. et al. (1 more author) (2009) The Adaptive Control of FES-assisted Indoor Rowing Exercise. In: Proceedings of 2009 CACS International Automatic Control Conference. Proceedings of 2009 CACS International Automatic Control Conference, Nov. 27-29, 2009, Taipei, Taiwan. , Taipei, Taiwan .

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The Adaptive Control of FES-assisted Indoor Rowing Exercise

Z. Hussain, M.A. Zaidan, M.O. Tokhi and R. Jailani

Department of Automatic Control and System Engineering
The University of Sheffield
United Kingdom
E-mail: cop06zh@sheffield.ac.uk

Abstract — **This paper describes the development of an adaptive control mechanism for FES-assisted indoor rowing exercise (FES-rowing). The FES-rowing is introduced as a total body exercise for rehabilitation of function of lower body through the application of functional electrical stimulation (FES). A model of the rowing ergometer with humanoid is developed using the visual Nastran software environment (vN4D). A fuzzy logic control (FLC) scheme is designed in Matlab/Simulink and adapted online by pre-training artificial neural network (ANN) to regulate the muscle stimulation pulse width required to drive FES-rowing. The ANN is used as an adaptation to the system that is required to account for muscle fatigue. The results signify that the adaptive control scheme is able to achieve and maintain better tracking performance. This study indicates that the adaptive control developed may provide an effective mechanism for automatically regulating the stimulation pulse width for FES-rowing to overcome muscle fatigue.**

Keywords — **Adaptive control; Fuzzy logic control; Artificial neural network; FES; Rowing exercise.**

I. INTRODUCTION

FES-assisted indoor rowing exercise (FES-rowing) is introduced as a physical activity through application of FES to assist paralyzed lower body movement that is combined with voluntary upper body movement [1-5]. It is a hybrid FES activity for rehabilitation of function of lower body for a person with spinal cord injury (SCI). It is introduced as a high intensity, safe, affordable and natural alternative total body exercise [6-8]. The development of FES-assisted indoor rowing exercise has become increasingly important as an alternative FES hybrid exercise. In FES-assisted indoor rowing exercise, FES is applied to the muscles for extension and flexion of hip, knee and ankle to perform the rowing exercise. Suitable electrical stimulation to the muscle is required in achieving a smooth and well coordinated rowing manoeuvre.

FES has been shown to improve impaired function and muscle deterioration in paralyzed limb of SCI patients. However, one of the major limitations is that the stimulated muscles tend to fatigue very rapidly, which limit the role of FES especially in rowing exercise [9]. Similar to other hybrid FES activity, the performance of FES-rowing can be enhanced through the implementation of efficient control strategy. Davoodi et al. [2] and Wheeler et al. [1] implemented the patient-driven control

of FES- rowing with fixed electrical stimulation intensities and only controlled the coordination of voluntary upper body and FES generated movements. This may result in early fatigue as patient tends to over stimulate the muscles. Later in 2002, Davoodi et al. [10] implement automatic finite states control to regulate the stimulation intensities and coordination of voluntary and FES generated movements. This may introduce over-stimulation to the paralyzed muscles and cause early fatigue and limit the duration of exercise.

Many researchers investigated various control strategies to address the variability and nonlinearities of the musculoskeletal system, muscle conditioning and fatigue in many different FES-activities [11-12]. One of the possible methods is the use of closed-loop and adaptive control technique that measures the output and alters the muscle stimulation for better control. Veltink [13] proposed an adaptive PID feedback control for cyclic movement but the slow adaptation introduced high initial error. Hatwell et al. [14] used a model–reference adaptive control for the same task, cyclic movement but ended up with difficulties in modelling the nonlinearities of musculoskeletal systems and even was limited to small frequency range of movement. Chang et al. [15] used adaptive neural network to track a cyclic movement. The neural network was trained offline to learn the inverse dynamics of the quadriceps muscle. The system required substantial input/output data for the network to be trained thoroughly during its off-line operation. Riess and Abbas [16] investigated adaptive neural network control to automatically adjust the stimulation patterns to suit the needs of a particular user and reduce the effect of muscle fatigue on the control system performance for cyclic movement. Their simulation study showed the ability of the controller to adapt a stimulation pattern for different musculoskeletal system. To the author's knowledge, none of the researchers has implemented such control strategies to reduce muscle fatigue in FES-rowing.

This paper presents adaptive control for FES-rowing in order to reduce the effect of the muscle fatigue by adaptation of muscle stimulation pulse width required to drive FES-rowing using fuzzy logic control (FLC) adapted by pre-training artificial neural network (ANN). The model of the FES-rowing was developed using the visual Nastran software (vN4D) software environment and link with the FLC and ANN that are implemented in the Matlab/Simulink environment.

II. DESCRIPTION OF THE MODEL

A. FES-rowing model

The FES-rowing model developed comprises two parts: rowing ergometer and humanoid model. They are designed using the vN4D environment. The humanoid model was developed using the anthropometric data based on Winter's work, and the details are provided in a previous work [17]. The machine is designed based on the modified indoor rowing machine that incorporates all its basic parts. A new seating system was developed which has high backrest to stabilize the trunk. The seat is attached to a horizontal rail via sliding constraint for smooth horizontal motion. A flywheel attached with sprocket is designed to provide damper resistance for pulling phase as shown in Fig. 1.

Fig. 1. Indoor rowing machine with humanoid model.

B. Physiological based muscle model

In order to simulate FES, a physiological based muscle model was constructed based on Riener and Fuhr's work [18]. The model describes the major properties of muscle and segmental dynamics of human during FES-rowing. Two groups of muscle for knee extension (quadriceps) and flexion (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: recruitment characteristic, frequency characteristic, calcium dynamics and muscle fatigue.

The muscle contraction accounts for the 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 obtained from the product of moment arm and muscle force. The passive muscle properties are divided into two components: passive elastics, $M_{ela,j}$ and passive viscous joint moments, $M_{vis,j}$. The specific parameters of the muscle and independent parameters of muscle and the performance of the developed muscle model in indoor rowing exercise are described in [19].

III. IMPLEMENTATION OF CONTROL STRATEGY

A specific control strategy is required to regulate the stimulated pulse width required by muscle model in order to obtain smooth rowing manoeuvre. The block diagram of the control system is illustrated in Fig. 2. This adaptive control consists of fuzzy logic control (FLC) feedback controller and artificial neural network (ANN) which is designated as an adaptive neurofuzzy controller. The plant to be controlled is represented by FES-rowing. First, the supervised learning ANN is used to find the input/output coincidence relations with minimum error using a back propagation algorithm. The network is trained in an offline mode. Once the network has been successfully trained, it would be used directly to adjust the FLC online. For a given desired reference trajectory of FES-rowing, the ANN could calculate the required weight to adjust the FLC to regulate the stimulation pulse width required by the muscle model to drive the FES-rowing.
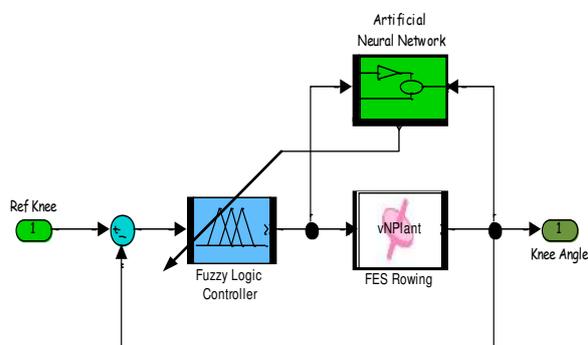

Fig. 2. Block diagram of adaptive neurofuzzy control system

A. Artificial neural network design

The ANN is a type of computation inspired by biological model. There are two phases involved in developing an ANN; learning and application. Learning is accomplished before ANN is ready to be used. It can be determined by a learning regime and can be different from each other. ANN aims to modify the weights for minimizing the response error. In this adaptive control, backpropagation neural network is used as the training method (see Fig. 3). Before training stage of the ANN, sufficient data, consisting of four input and output parameters, is acquired by simulating the system at different muscle fitnesses in both of muscle; quadriceps and hamstrings (see Fig. 4).

The stimulation pulse width required for each of the muscle fitness parameter change is recorded as output parameters of ANN. A total of 30 data sets were obtained through this process for training purposes. It is essential for the learning rate η, number of epochs (iteration), hidden nodes (the number of neurons) and number of hidden layers to be tuned in order to achieve rapid learning during the teaching process. Several combinations of these parameters can be applied to attain the convergence of error and also the respective optimal values.
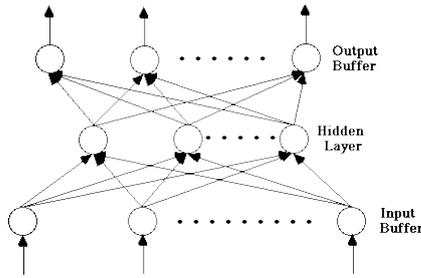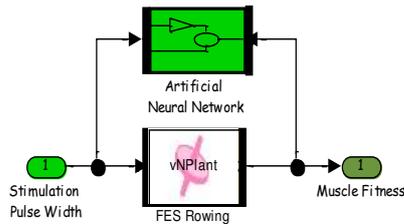
Fig. 3. Backpropagation ANN

Fig. 4. Block diagram of ANN learning process

B. Fuzzy logic control design

In this study, four fuzzy logic controllers are designed to control knee extensors and flexors for both legs. There are four inputs selected for the controller, comprising the error (difference between actual knee trajectory and reference knee trajectory), change of error and knee angular velocity and acceleration. The error and change of error are measured from the vN4D FES-rowing simulation model. The outputs are the stimulation pulse widths for quadriceps and hamstrings muscles. Five Gaussian type equally distributed membership functions are used for each input, error and change of error and the output as described in previous work [20]. Fig. 5 shows the block diagram of the FLC designed for FES-rowing.
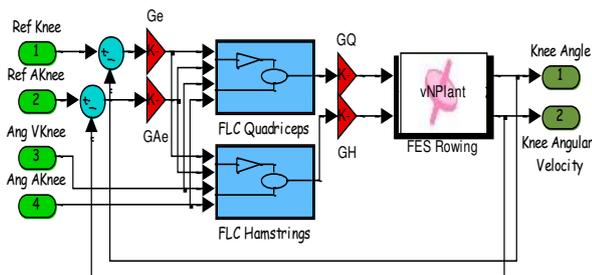

Fig. 5. Block diagram of FLC without adaptation

C. Adaptive neurofuzzy description

The stimulation pulse width generated by FLC is adjusted by the ANN before transmission to the muscle. The ANN is used to adaptively adjust the two output scaling factor of the FLC. In the adaptive neurofuzzy scheme, the fitness function of quadriceps and hamstrings muscles (MFq and MFh) are measured and processed by ANN model as input. When the trained

ANN observes a change in muscle fitness function, a new weighted value of the ANN is calculated and submitted to the FLC and the output of scaling factor is substituted with the new weighted value. This new value is then multiplied with the crisps value of FLC to obtain the adapted stimulation pulse width to be transmitted to both muscles. The weight adaptation is calculated in real-time as the control algorithm develops suitable stimulation pulse width.

IV. RESULT AND DISCUSSION

In the preprocessing phase, architecture identification of ANN was evaluated using test data. In the learning and training process, learning rate, the number of epochs and number of neurons were tuned within 0.1 to 0.9, 2000 to 20000 and 2 to 52 respectively to determine the best tuned set for optimal performance. Fig. 6 shows the input-output of the model estimated by ANN. Gradient descent training (traingd) was used as the learning rule while sigmoid function was used as the transfer function of activation function. During training sessions, the best performance of model was achieved with optimum values of learning rate, number of epochs and number of neurons as 0.3, 10000 and 52 respectively in one hidden layer. These parameters gave satisfactory result for the given test data.
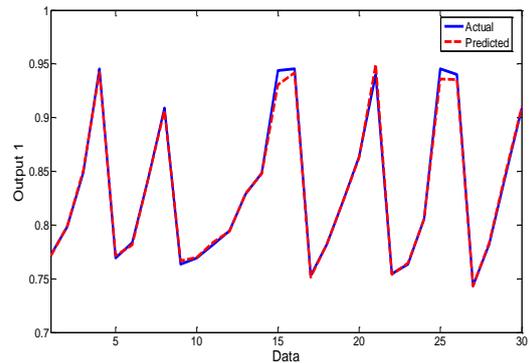

Fig. 6. Actual and predicted output by ANN

In this study, the knee and elbow trajectories are controlled (with predefined reference trajectories, Fig. 7) to provide a consistent rowing sequence. In order to evaluate the system performance, the FES-rowing is allowed to drive for 15 complete cycles.
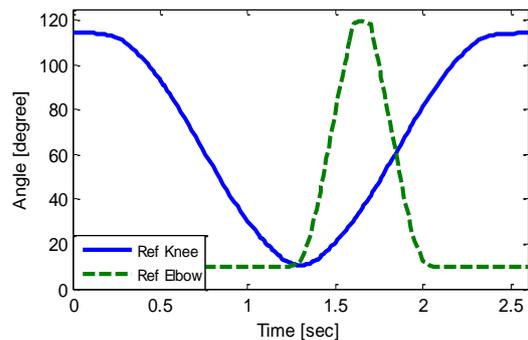

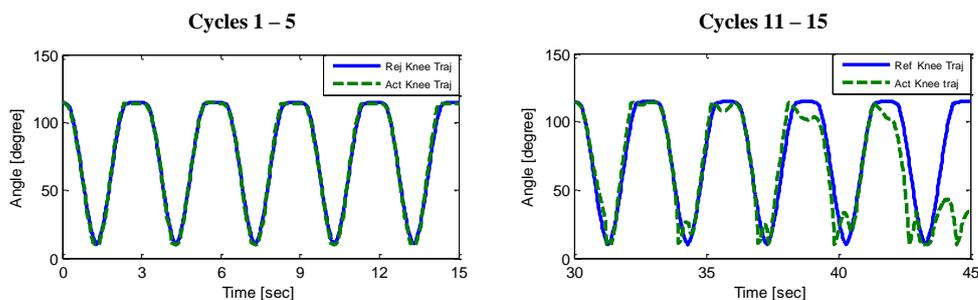Fig. 7. Knee and elbow reference trajectories

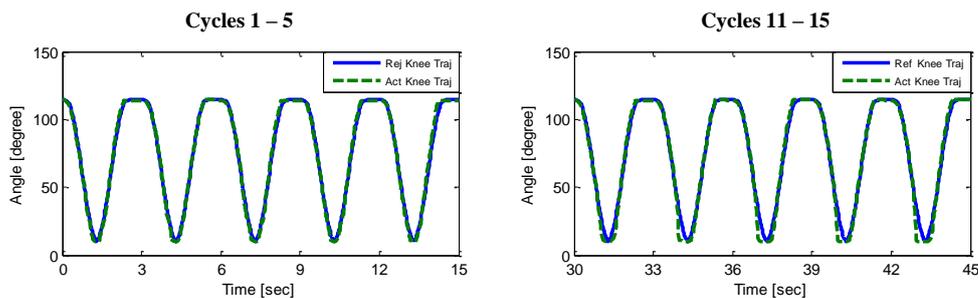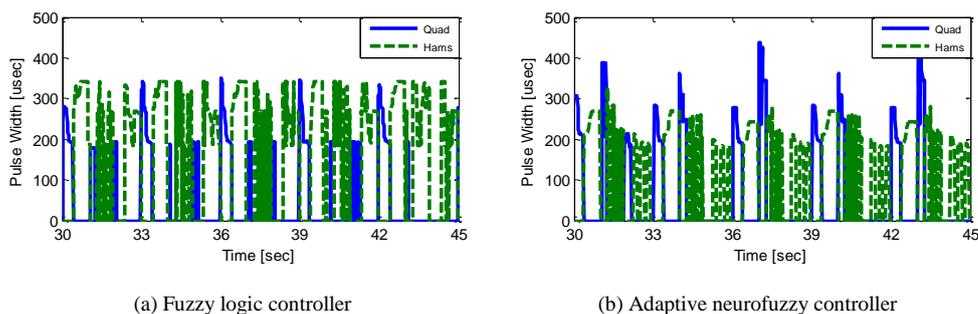Fig. 8. Knee trajectory with fuzzy logic control

Fig. 9. Knee trajectory with adaptive neurofuzzy controller

(a) Fuzzy logic controller   (b) Adaptive neurofuzzy controller

Fig. 10. Stimulated pulse width generated by the controller

Fig. 8 and Fig. 9 show the examples of knee trajectories from the simulation using the FLC alone and adaptive control evaluated on the FES-rowing performance. It was noted that, the actual knee trajectory followed the reference knee trajectory very well for the first 10 cycles (cycle 1-5 and 11-15 shown in Fig. 8) when fuzzy logic controller was used to regulate the stimulation pulse width. The knee trajectory started to diverge and did not track well after 11th cycle and became worth at 14th and 15th cycles. This may be due to muscle fatigue. The muscle fitness starts to significantly reduce after 11th rowing cycles. Fig. 9 shows the performance of the adaptive neurofuzzy controller implemented to overcome this muscle fatigue for FES-rowing. It was noted that the actual knee trajectory followed the reference knee trajectory very well from the very first cycle till the 15th cycle (cycle 1-5 and 11-15 shown in Fig. 9). The controller was able to adjust the regulated pulse width of the FLC to compensate for muscle fatigue.

Fig. 10 shows the stimulation pulse width regulated by both the FLC and adaptive neurofuzzy controllers. Fig. 10(a) shows the stimulation pulse width generated by

FLC. It can be seen that almost the same stimulation pattern was generated by FLC for the 11th to 15th cycles of FES-rowing although muscle fatigue had occurred. The average quadriceps muscle stimulation pulse width was recorded at 47.9μsec and the average hamstrings stimulation pulse width recorded was 138.4μsec.

The stimulation pulse width generated by adaptive neurofuzzy controller is shown in Fig. 10(b). It can be seen that different stimulation pattern was generated by the controller for all 5 FES-rowing cycles (11th to 15th cycles) especially the quadriceps muscle stimulation pulse width. The different stimulation pattern generated may be related to different levels of muscle fatigue observed by the ANN in the adaptive controller. The average quadriceps muscle stimulation pulse width was recorded at 56.6μsec and the average hamstrings stimulation pulse width recorded was 105.4μsec. Note that the average stimulation pulse width generated by adaptive neurofuzzy controller for hamstrings muscle was significantly reduced compared to FLC by 33μsec. But the average stimulation pulse width generated for quadriceps muscle was increased by 8.7μsec. This may be due to the

adjustment made by adaptive neurofuzzy controller to compensate for the reduced of stimulation pulse width required by hamstrings muscle as a weak muscle group.

V. CONCLUSION

The present study has established the performance of FES- rowing with adaptive control to account for muscle fatigue. The results show that the adaptive control implemented has significantly improved the FES-rowing performance when the muscle fitness decreased compared to the performance with FLC alone. The adaptive controller made some adjustment to the stimulation pattern for both quadriceps and hamstrings muscle to deal with muscle fatigue by reducing the stimulation required by hamstrings muscle. These results indicated that the adaptive neurofuzzy controller was able to automatically account for individual muscle properties in generating the stimulation pulse width required to perform FES-rowing. Further work with extensive FES-rowing cycles will be carrying out to fully assess FES-rowing performance with this adaptive control scheme.

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