LETTER

An Effective Method on Applying Feedback Error Learning Scheme to Functional Electrical Stimulation Controller

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SUMMARY A Feedback Error Learning (FEL) scheme was found to be applicable to joint angle control by Functional Electrical Stimulation (FES) in our previous study. However, the FEL-FES controller had a problem in learning of the inverse dynamics model (IDM) in some cases. In this paper, methods of applying the FEL to FES control were examined in controlling 1-DOF movement of the wrist joint stimulating 2 muscles through computer simulation under several control conditions with several subject models. The problems in applying FEL to FES controller were suggested to be in restricting stimulation intensity to positive values between the minimum and the maximum intensities and in the case of very small output values of the IDM. Learning of the IDM was greatly improved by considering the IDM output range with setting the minimum ANN output value in calculating ANN connection weight change.
key words: *functional electrical stimulation, FES, feedback error learning*

1. Introduction

Functional Electrical Stimulation (FES) has been found to be effective clinically in assisting or restoring paralyzed motor functions caused by spinal cord injury or celebrovascular disease. One of main topics of FES research work is to realize the controller that restores movements appropriately and stably. We developed a multi-channel proportional-integral-derivative (PID) controller that could provide a way of solving ill-posed problem in regulating stimulation intensities [1], [2].

The PID controller made it possible to apply the Feedback Error Learning (FEL) scheme [3] to FES control. FEL controller for FES (FEL-FES controller) includes feedforward and feedback controllers. The feedforward controller is realized by training artificial neural network (ANN) by using outputs of the feedback controller as teacher signals. The feasibility of the FEL-FES controller was found through the experimental tests of 1-DOF movement control of the wrist joint with able bodied subjects [4]. In some cases, however, output power of the feedback controller did not decrease to small value. Further iteration of learning of the ANN in such cases even caused increasing error and output power of the feedback controller, and decreasing output power of the feedforward controller.

This paper focused on finding a possible solution for the problem. Computer simulation tests of some methods of applying the FEL to FES control were carried out on controlling wrist joint movement stimulating 2 muscles with several subject models under several control conditions.

2. Feedback Error Learning Controller for FES

The feedback error learning controller for FES examined in this study is shown in Fig. 1. The sum of stimulation outputs from the feedforward controller (inverse dynamics model, IDM) and the PID controller is applied to each muscle after adding offset (threshold value of electrical stimulation intensity) and clipping out with the limiter to prevent excessive stimulation.

Four-layered ANN was used for the IDM [4]. The ANN was trained online by the error back-propagation algorithm using the outputs of the PID controller. Inputs for the IDM was target angles, angular velocities and angular accelerations of the target movements. The data at continuous 6 times, from t to $t + 5$ (50 ms interval), were given to neurons in the input layer simultaneously.

The PID controller outputs positive and negative values of stimulation intensities. In controlling muscle contraction by FES, negative value of the controller output is not be used. However, both positive and negative outputs of the PID controller are necessary to train the ANN by using the FEL. The output function of neurons in the second and third layers of the ANN is the sigmoid function that outputs values between 0 and 1. The connection weights between the first and the second layers, and between the second and the third layers were adjusted in the learning. The connection weights between the third and the fourth layers were fixed at $(S^i_{max} - S^i_{min})$. S^i_{max} and S^i_{min} shows maximum and minimum intensities for muscle i, respectively.

The PID control algorithm used in the FEL-FES con-

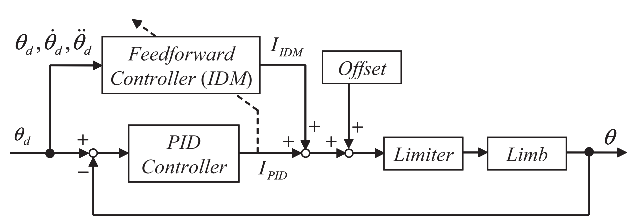

Fig. 1 Feedback error learning controller tested in this study. The inverse dynamics model (IDM) was used for the feed-forward controller.

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troller was described by the following equation using stimulation intensity vector $\boldsymbol{S}_n$ [1]:

$$\boldsymbol{S}_n = \boldsymbol{K}_P\,\boldsymbol{e}_n + \boldsymbol{K}_I \sum_{i=0}^{n} \boldsymbol{e}_i + \boldsymbol{K}_D(\boldsymbol{e}_n - \boldsymbol{e}_{n-1})$$

The error vector $\boldsymbol{e}_n$ is defined by difference between target and measured joint angle vectors at time n. $\boldsymbol{K}_P$, $\boldsymbol{K}_I$ and $\boldsymbol{K}_D$ are PID parameter matrices [1].

3. Computer Simulation Test of Applying Methods of the FEL-FES Controller

3.1 Applying Methods of FEL to FES

Through observation of learning process in preliminary computer simulation tests, insufficient learning was considered to be caused by restricting controller output to positive values between the minimum and the maximum intensities and in the case of very small output values of the IDM. Negative output of the PID controller when IDM output is very small and positive one when IDM output is almost maximum have no effect on ANN training. In the case of very small output of the IDM, change of ANN connection weights is very small, and therefore, the learning can not be effective with positive output of the PID controller. These can be problems in applying the FEL to FES control.

In this paper, using output values of neurons in the third layer of ANN, S_{ANN}, and PID controller, S_{PID}, the following 4 applying methods of the FEL were examined:

1) previous method [4].
2) if ($S_{ANN} < 0.01$ and $S_{PID} < 0$) or ($S_{ANN} > 0.99$ and $S_{PID} > 0$) then change of ANN connection weight is 0 in the method 1).
3) if ($S_{ANN} < 0.1$ and $S_{PID} < 0$) or ($S_{ANN} > 0.99$ and $S_{PID} > 0$) then change of ANN connection weight is 0 in the method 1).
4) in addition to the method 2), if ($S_{ANN} < 0.1$ and $S_{PID} > 0$) then calculate ANN connection weight change using $S_{ANN} = 0.1$.

S_{ANN} can be calculated from IDM output (output of neurons in the fourth layer of ANN), S_{IDM}, by linear transformation. In the method 4), real value of S_{ANN} was used when the controller output was calculated. $S_{ANN} = 0.01$ means that if S_{PID} is less than 0, output of the FEL-FES controller is about the threshold value S_{min}. $S_{ANN} = 0.1$ was determined to produce output value of the FEL-FES controller less than about $1.2 \times S_{min}$ when S_{PID} is negative value.

3.2 Computer Simulation Method

ANN learning and control performance was examined by computer simulation using the musculoskeletal model [5]. The musculoskeletal model to predict responses of electrically stimulated muscles were developed including nonlinear characteristics and dynamics. Six different subject models were prepared, whose model parameters were adjusted to represent approximately muscle responses to electrical stimulation of 6 neurologically intact subjects, respectively.

FES control was performed on sinusoidal movement of the wrist joint in the dorsi/palmar flexions. Stimulated muscles were the extensor carpi radialis longus/bravis, which were assumed to be one muscle group (ECR), and the flexor carpi ulnaris (FCU). The ANN was trained on different 3 target trajectories, in which the center of the sinusoidal angle trajectory was changed (0 deg, 5 deg in palmar flexion and 5 deg in dorsi flexion). The joint angle range was 15 deg both for dorsi and palmar flexions from the center. Three cycle periods, 2, 3 and 6 s, were used for each trajectory. Three sets of random initial values of the ANN connection weights that did not produce large outputs for unlearned ANN were prepared. Therefore, the 4 applying methods were tested under 27 simulation conditions for each subject model. The joint angles were positioned at 0 deg for the first 5 s. Control outputs for the first 5 s were not used for the ANN training. Six cycles were included in one control trial for training. Iteration number of training was fixed at 50.

Learning speed coefficient for ANN connection weights between the 2nd and the 3rd layers was decreased as the ANN learning progressed properly as seen in our previous work [4]. The learning progress was evaluated by mean error (ME) and power ratio (PR). The ME was averaged absolute error between the target and controlled angles. The PR was calculated by the following equation in each control trial excluding the first 5 s:

$$PR = \frac{\sum P_{IDM}(t)}{\sum P_{PID}(t) + \sum P_{IDM}(t)} \times 100$$

where, P_{IDM} and P_{PID} represent output power of the IDM and the PID controller, respectively.

3.3 Results

Root-mean-square (RMS) value of output of PID controller and PR, and ME after ANN learning are shown in Figs. 2 and 3. ME is shown for each subject model for considering dependency on subject. Evaluation results using untrained ANN are shown in Table 1. In most of simulation conditions, the ANN learned dynamic characteristics of the controlled object successfully. Values of ME decreased after ANN training. Small RMS values of PID output and large PR shows that the tracking control was mainly performed by the IDM.

In some cases using the previous method of applying the FEL, outputs of the PID controller could not be decreased sufficiently. This is found in Fig. 2 as larger RMS values and small values of minimum PR. Figure 4 indicates an example of control result by the FEL-FES controller. In the case of the previous method 1), although controlled joint angles were improved in reducing delay, outputs of the IDM after learning were different from PID outputs before the learning, especially in the stimulation timing. That is, stimulation to both muscles were applied by the IDM at almost same timing after the learning. The PID controller worked

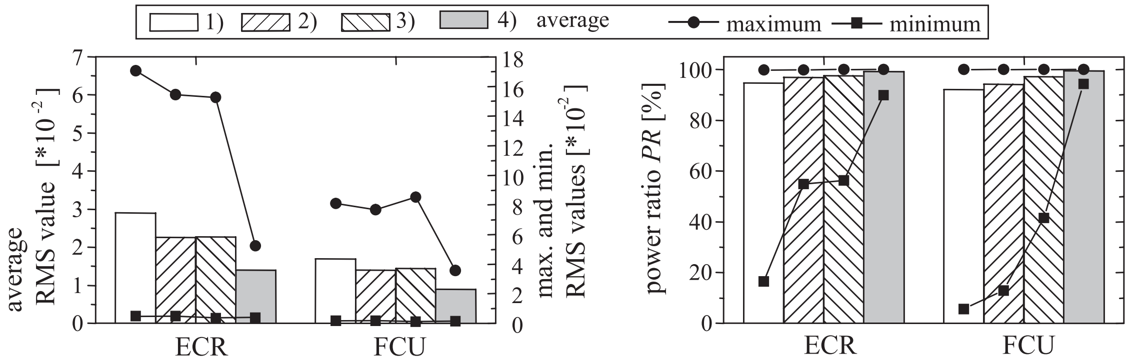

Fig. 2 RMS values of PID controller output and power ratio (PR) after ANN learning. Average, maximum and minimum values for all the control conditions are shown.

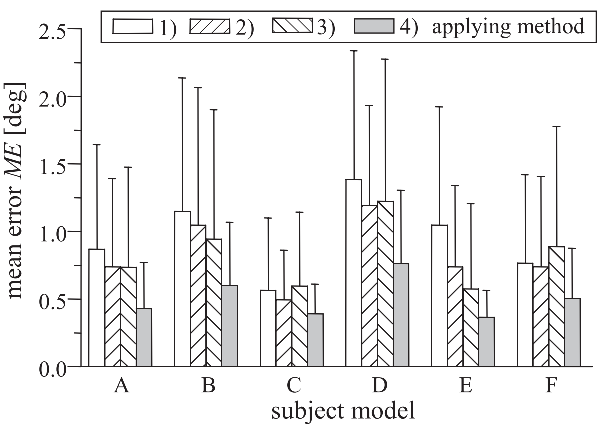

Fig. 3 Mean error (ME) during the control by the FEL-FES controller after ANN learning. Average and standard deviation are shown.

Table 1 Evaluation results before ANN learning.

		average	min	max
ME [deg]		4.51 ± 1.55	1.81	8.80
RMS [$\times 10^{-2}$]	ECR	19.5 ± 6.8	7.1	45.7
	FCU	10.7 ± 3.6	2.7	20.4
PR [%]	ECR	9.1 ± 14.8	0.1	71.1
	FCU	5.9 ± 7.7	0.2	48.0

in order to compensate the error in this case. The insufficient learning were caused in 23 of 162 simulation conditions (14.2%). Applying the method 4), the outputs of the PID controller were decreased appropriately and the IDM produced similar amplitude pattern as the PID controller before the training.

The modified methods of applying the FEL 2)–4) almost achieved smaller ME, smaller RMS value of PID output, and larger PR than those of the previous FEL-FES controller. The methods 2) and 3) were basically effective, but the method 3) was sometimes not useful compared to the previous FEL application method because of increasing ME and RMS value as seen in Fig. 3. The method 4) was effective for all the subject models showing great improvement of ME, RMS values and PR.

4. Discussions

The FEL-FES controller developed in the previous study [4] was confirmed to be feasible, but it was found not to be sufficient in applying to FES control. The method 4) improved significantly the ME, RMS values and PR, while the methods 2) and 3) improved them slightly. There was no insufficient learning of the IDM such as seen in Fig. 4 (b) by using the method 4). Considering output range of the IDM with setting the minimum output value of the ANN in calculating change of ANN connection weights were highly effective to train ANN. Ignoring negative output of the feedback controller in the ANN learning was also suggested to limit to very small output value of the ANN.

It is possible to avoid including constraints used in the methods 4), if outputs of the IDM have both positive and negative output values. Although it may be possible to use the negative value for IDM output considering antagonistic muscle pair, it is not practical because antagonistic muscle can not be fixed or defined for all muscles. Therefore, output value of the IDM has been limited to positive value in our studies and the method 4) would be reasonable and practical in learning of the IDM for FES. Realizing the IDM whose outputs involve the threshold of stimulation intensity is considered as an alternative method. However, it is necessary to determine the threshold value for the ANN from the real threshold intensity. The results of this paper will provide useful information in such translation.

5. Conclusion

Methods of applying the feedback error learning (FEL) scheme to FES control were examined in controlling 1-DOF movements of the wrist joint through computer simulation. Learning of the IDM was greatly improved by considering the IDM output range with setting the minimum ANN output value in calculating ANN connection weight change. It is expected to test the modified application method for more complicated system that includes more control targets and more stimulated muscles.

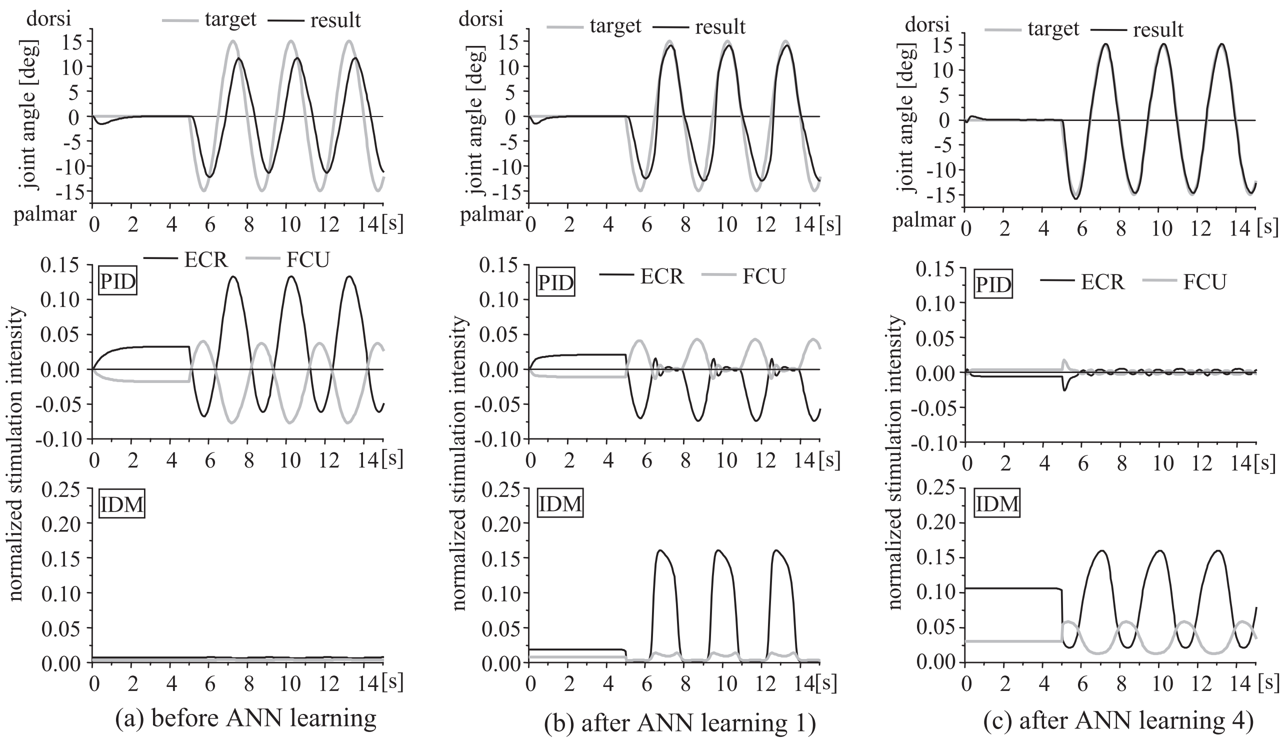

Fig. 4 An example of control result by the FEL-FES controller using the previous application method and the modified methods 1) and 4) (subject model D, origin is in the center, 3 s of cycle period). The first 15 s are shown. After the ANN training, ME was 2.84 deg, RMS values were 10.19 and 6.87 [$\times 10^{-2}$], and PR were 81.1 and 9.7% for (b), ME was 0.55 deg, RMS values were 1.11 and 0.68 [$\times 10^{-2}$], and PR were 99.86 and 99.77% for (c), respectively.

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