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Compensation of the Effects of Muscle Fatigue on EMG-Based Control using Fuzzy Rules Based Scheme*

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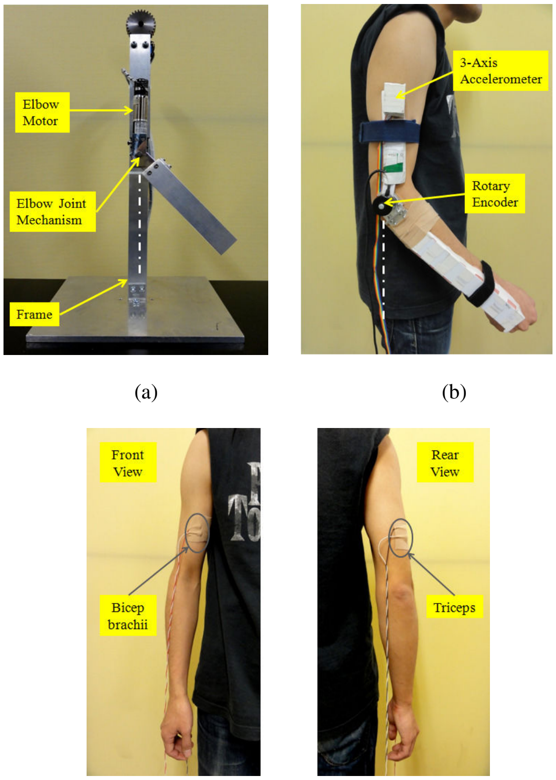
Abstract— **Estimation of the correct motion intention of the user is very important for most of the Electromyography (EMG) based control applications such as prosthetics, power-assist exoskeletons, rehabilitation and teleoperation robots. On the other hand, safety and long term reliability are also vital for those applications, as they interact with human users. By considering these requirements, many EMG-based control applications have been proposed and developed. However, there are still many challenges to be addressed in the case of EMG based control systems. One of the challenges that had not been considered in such EMG-based control in common is the muscle fatigue. The muscle fatiguing effects of the user can deteriorate the effectiveness of the EMG-based control in the long run, which makes the EMG-based control to produce less accurate results. Therefore, in this study we attempted to develop a fuzzy rule based scheme to compensate the effects of muscle fatigues on EMG based control. Fuzzy rule based weights have been estimated based on time and frequency domain features of the EMG signals. Eventually, these weights have been used to modify the controller output according with the muscle fatigue condition in the muscles. The effectiveness of the proposed method has been evaluated by experiments.**

I. INTRODUCTION

During last decade medical and human welfare robots have gained a lot of attention because those technologies can be used to improve the quality of life of the people. The devices such as exoskeletons, prosthetics, teleoperation robots, rehabilitation robots can be considered as common applications in the biorobotics field. On the other hand, electromyography (EMG) is one of the biological signals that are commonly used as a controller input signal in those kinds of applications because it reflects the activity level of the muscles. Real-time estimation of the correct motion intention of the user is very important for EMG-based control because those applications usually interact with the human. Many examples which use the EMG signal as control input can be found under each application. Exoskeletons are one of such applications which are typically used for power assist purposes of physical weak disabled or injured persons. Many types of exoskeleton robot have been developed for various purposes [1], [2]. On the hand, rehabilitation robots have been proposed in order to help the rehabilitation procedures [3], [4] and sometimes exoskeleton robots have been used as the rehabilitation robots as well. However, those exoskeleton or rehabilitation robots may not be useful for individuals who do not have their full or partial limbs. Therefore, many prosthetic devices have been proposed for such amputees depending on their requirements [5], [6]. Another type of devices that use the EMG-based control methods are the teleoperation robots [7].



(a) (b)

(c)

Fig. 1 (a),(b) Experiemental setup (c) locations of the EMG electrodes placed on bicep and tricep muscles of the upper-limb

However, controlling various applications based on EMG signals as mentioned above is a challenging task due to several reasons. EMG signal is a biological signal so that it is difficult to observe the same EMG signal for the same motion even with the same person. Also EMG signal shows inter variability between each user and roles of the each muscle for a certain motion vary with the upper-limb posture. To cope with these problems several promising controller methods have been proposed based on adaptive control techniques [2], [5]. However, one of the problems that often come across with the EMG-based control methods are the muscle fatigue. Generally, muscle fatigue can occur to any user who uses such EMG-based applications. Consequently, there is a high probability of muscle getting fatigued for physically weak, disabled or old persons as a result of physical exhaustion throughout the day. Therefore an EMG-based controller which has not adapted to the changes of EMG signals caused by the effects of muscle fatigue may not estimate the accurate

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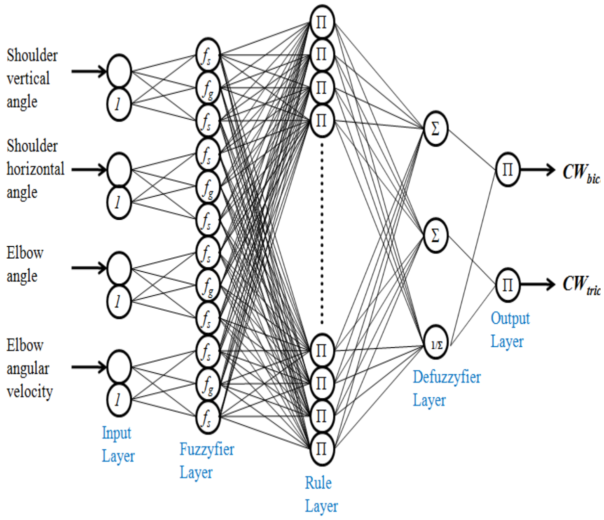

Fig. 2 Structure of the fuzzy-neuro modifier used to estimate the coefficients, CW_{bicep} and $CW_{triceps}$

motion intention during the muscle fatigue conditions. One of the possible solutions to cope this problem is to design an EMG-based control method which is robust to the time-varying or non-stationary EMG signals. In fact , there are few attempts can be found which proposed to deal with the non-stationary behavior of the EMG signals, especially due to the muscle fatigue in EMG based control [8].

In this paper, a fuzzy rule based scheme is proposed to compensate the effects of muscle fatigue on EMG-based control. A set of fuzzy rules based on EMG Root Mean Square (RMS) and Mean Power Frequency (MPF) features are used to estimate weights which correspond to the level of the muscle fatigue condition of the each muscle. Then, these estimated weights are used to modify the EMG-based torque estimation according to the muscle fatigue condition of the muscles. The proposed method allows more correct estimation of the EMG-based torque and compensates the effects of muscle fatigue on EMG-based control during the muscle fatigue situations. The effectiveness of the proposed method is evaluated by performing experiments.

II. METHOD

The effectiveness of the proposed method is evaluated based on a robot arm which mimics or operates according to the elbow flexion/extension motion of the human subject. The subject is asked to perform the elbow motions in the sagittal plane and the robot is supposed to move according to the desired elbow motion of the subject. The biceps brachii and the triceps muscles are used to measure the EMG signals because those two muscles are typically the most contributed muscles for elbow flexion/extension motions. The EMG signals are measured using surface EMG electrodes in a bipolar montage at a sample rate of 2 kHz. The experimental robot and the locations of the EMG electrodes placed on the upper-limb of a user are shown in Fig.1 (a) and (c), respectively. As an EMG raw signal is not ideal to use in the EMG-based control method, the Root Mean Square (RMS) of the EMG signal is calculated as shown in the following equation.

$$ch_i = \sqrt{\frac{1}{N}\sum_{j=1}^{N} v_{ij}^2} \tag{1}$$

Where ch_i is the RMS value of ith channel EMG signal, v_{ij} is the voltage of ith channel at jth sampling. N is the number of the segments (N=100). EMG-based joint torque is estimated based on RMS values and it is estimated for elbow joint as follows.

$$\tau_{elbow} = w_{elbow.bicep}.ch_{bicep} + w_{elbow.triceps}.ch_{triceps} \tag{2}$$

Where τ_{elbow}, ch_{bicep}, and $ch_{triceps}$ are EMG-based elbow torque, EMG RMS of biceps brachii muscle and EMG RMS of the triceps muscle, respectively. The weights, $w_{elbow.bicep}$ and $w_{elbow.triceps}$ are the corresponding weights related to bicep brachii and triceps muscles which are changed according to a fuzzy-neuro modifier. This fuzzy-neuro modifier is applied to take into account the effects of upper-limb posture differences of the user [2], [5]. The structure of this fuzzy-neuro modifier which is used is shown in Fig. 2. Shoulder vertical, horizontal angles, elbow joint angle and angular velocity are fed into the fuzzy-neuro modifier as the inputs. Elbow angle and shoulder angles are measured at rate of 2 kHz using a rotary encoder and a 3-axis accelerometer, respectively. That set up is shown in Fig.1 (b). Final weight values are obtained by the product of initial weight values (which are set to 1 initially) and the CW_{bicep}, $CW_{triceps}$. However, it is important to train this fuzzy-neuro modifier. Therefore error back-propagation algorithm is applied to minimize the squared error between measured user's elbow angle and robot joint angle. During the training process, the subject is asked to perform the elbow flexion/extension motions while holding a 2kg weight in their hand. Several short periods of training sessions are conducted instead of a long training period in order to avoid the muscle fatigue conditions. If the fuzzy-neuro modifier works well, the generated robot motion and the user's motion are supposed to be similar. However, the main aim of this paper is to evaluate the fuzzy rule based scheme for compensating the effects of muscle fatigue on EMG-based control. Therefore, the effectiveness of the previously explained fuzzy-neuro modifier is not going to evaluate through this paper. It has been already evaluated in the previous papers [2] , [5]. But, the estimation of the EMG-based torque in (2) does not consider the effects of muscle fatigue.

In order to influence the muscle fatigue conditions of the each muscle, the EMG-based torque estimation in (2) is modified as follows.

$$\begin{aligned}\tau_{elbow.FC} &= w_{elbow.bicep}.ch_{bicep}.w_{BFC} \\ &+ w_{elbow.triceps}.ch_{triceps}.w_{TFC}\end{aligned} \tag{3}$$

Where w_{BFC} and w_{TFC} are the two new weights which are estimated according to proposed fuzzy rule based scheme in this study. The EMG RMS and a frequency domain feature Mean Power Frequency (MPF) are used as the inputs of this fuzzy rule based scheme because amplitude and spectral frequency characteristics have been often used to monitor the muscle fatigue [9] -[11]. EMG MPF is the frequency of the EMG signal at which the average power within the segment/window is reached. To calculate the MPF, the Power Spectrum Density (PSD) of the EMG signals is calculated using Fast Fourier Transformation (FFT) method.

Table I. Example of fuzzy rules for w_{BFC}

RULE	IF	THEN
1	RMS = VS and MPF = VS	$w_{BFC} = 0.8$
2	RMS = VS and MPF = S	$w_{BFC} = 0.9$
3	RMS = VS and MPF = L	$w_{BFC} = 1.0$
4	RMS = VS and MPF = VL	$w_{BFC} = 1.0$
5	RMS = VS and MPF = UL	$w_{BFC} = 1.0$
6	RMS = S and MPF = VS	$w_{BFC} = 0.75$
7	RMS = S and MPF = S	$w_{BFC} = 0.85$
8	RMS = S and MPF = L	$w_{BFC} = 0.95$
9	RMS = S and MPF = VL	$w_{BFC} = 0.95$
10	RMS = S and MPF = UL	$w_{BFC} = 1.0$
11	RMS = L and MPF = VS	$w_{BFC} = 0.7$
12	RMS = L and MPF = S	$w_{BFC} = 0.8$
13	RMS = L and MPF = L	$w_{BFC} = 0.85$
14	RMS = L and MPF = VL	$w_{BFC} = 0.95$
15	RMS = L and MPF = UL	$w_{BFC} = 1.0$
16	RMS = VL and MPF = VS	$w_{BFC} = 0.65$
17	RMS = VL and MPF = S	$w_{BFC} = 0.75$
18	RMS = VL and MPF = L	$w_{BFC} = 0.85$
19	RMS = VL and MPF = VL	$w_{BFC} = 0.95$
20	RMS = VL and MPF = UL	$w_{BFC} = 1.0$
21	RMS = UL and MPF = VS	$w_{BFC} = 0.6$
22	RMS = UL and MPF = S	$w_{BFC} = 0.7$
23	RMS = UL and MPF = L	$w_{BFC} = 0.8$
24	RMS = UL and MPF = VL	$w_{BFC} = 0.9$
25	RMS = UL and MPF = UL	$w_{BFC} = 1.0$

The MPF is calculated as follows:

$$MPF = \frac{\sum_{i=1}^{M} f_i . PSD_i}{\sum_{i=1}^{M} PSD_i} \qquad (4)$$

Where PSD_i is i^{th} line of the EMG power spectrum density, f_i is the i^{th} frequency bin of the power spectrum density and M is the length of the power spectrum density (M=1024). The MPF is calculated at every 128 data points (approximately 50ms) and the same value is kept until the next value is calculated in order to synchronize with the EMG RMS sample rate. The IF-THEN rules of fuzzy-rule based scheme is prepared based on pre preliminary experiments. In these experiments elbow flexion/extension motions are performed by each subject, allowing the robot to move according to the estimated torque as in (2). However, in this case the subjects are asked to carry on the motion until they feel muscle fatigue. The values of five linguistic variables (VS, S, L, VL and UL) for each EMG RMS,MPF of the two muscles and fuzzy rules are decided by examining those preliminary experimental results (EMG RMS,MPF, EMG-based torque and the robot joint angle) of each subject. Two nonlinear functions (i.e. Gaussian function for S, L, VL and Sigmoid function for VS, UL) are used to express the membership functions of EMG RMS and MPF features. Therefore, 25 rules for each bicep and triceps are used for estimating the w_{BFC} and w_{TFC}, respectively. An example of such fuzzy IF-THEN rules for w_{BFC} are shown in Table I. To use the proposed fuzzy rule based scheme for compensation of the effects of muscle fatigue, $\tau_{bicep.\ FC}$ is used to estimate the EMG-based torque.

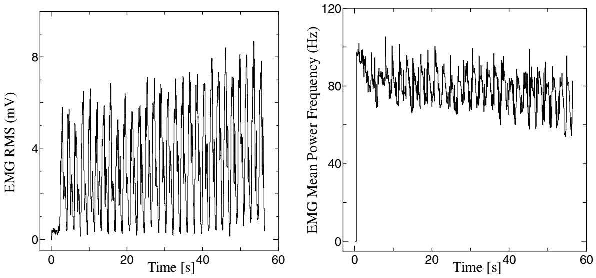

Fig. 3 Sample variations of EMG RMS and MPF for bicep of subject B

III. EXPERIMENTS AND RESULTS

In order to evaluate the effectiveness of the proposed method, experiments have been carried out and three healthy young male subjects (A: 27 years B: 24 years and C: 23 years) performed elbow flexion/extension motions while holding a 2kg weight in their hand to control the robot using EMG signals. Each subject was asked to perform the elbow flexion/extension motions until they felt fatigued .

Fig. 3 depicts a sample EMG RMS and EMG MPF features variation during an experimental session of the subject B. It can be seen that, EMG RMS shows an increasing pattern whereas EMG MPF decrease to lower frequencies which is an indication of muscle fatiguing conditions [9] -[11]. Even though different patterns suggest with each subject in the EMG RMS and MPF in different levels of fatigue conditions of biceps and triceps muscles, the proposed fuzzy rules should be able to cope with it since they were decided carefully in the preliminary experiments. If the proposed method effectively estimates the correct torque output according to the desired motion of the subject in the muscle fatigue conditions, the robot should mimic the subject's desired elbow motion. However, it is important to test the results without the proposed fuzzy rule based scheme to get a proper evaluation of the effectiveness. To compare the robot motions between the system with and without fuzzy rule based scheme, it is necessary to check with respect to the similar input conditions. Therefore, EMG RAW signals, human elbow joint angles and the accelerometer data were recorded for each and every session during the experiments. To test the EMG based controller without the proposed fuzzy rule based scheme, the recorded data were fed into the program in real time and allowed the robot to move according to the generated EMG-based torque using (2).

Fig. 4 (a) shows the results of subject A during a sample 10[s] time period at the beginning of the motion. One can see that there is no such significant difference between the robot's motion with or without the proposed fuzzy rule based scheme. In both the cases, the controller was able to mimic according to the desired elbow motion because the subject was not in the muscle fatigue conditions. The average peak angle difference between the user and the robot, with and without fuzzy rule based scheme are 6 [deg] and 5 [deg] respectively during the 10 [s] period. Similar results were obtained with the other two subjects. However, Fig.4 (b) suggests the effectiveness of the proposed fuzzy rule based scheme for compensation for the effects of muscle fatigue.

The results for subject A, B and C during the sample periods of 10 [s] near to the end of the experiments are depicted in Fig.4 (b).

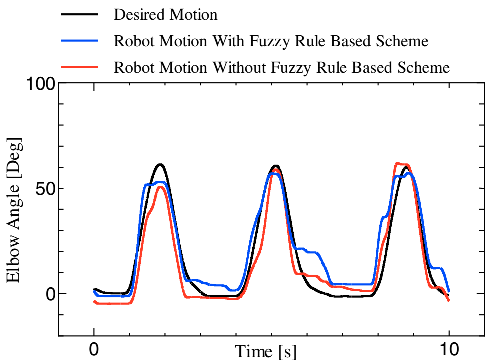

Fig.4(a) Example results for 10s near to the beginning of the motion experiment of subject A

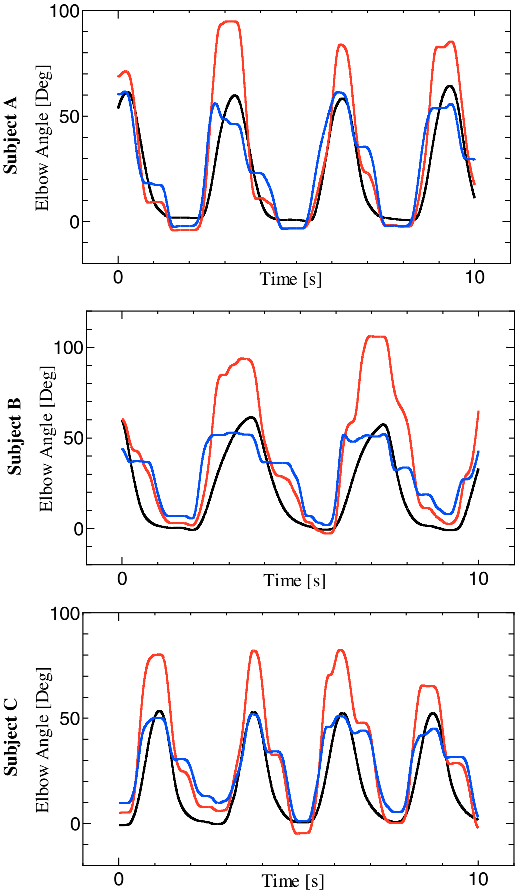

Fig. 4(b) Example results for 10s near to the ending of the motion experiments of subject A, B and C

It can be seen that for all the subjects, the motions of the robot without the proposed fuzzy rule based scheme have not able to correctly estimate the desired motion of the subjects. In this case the average peak angle difference between desired and the robot motion for subject A, B and C with this sample 10 [s] periods are 24 [deg], 38 [deg], and 27 [deg], respectively. The reason for this overshoot angle is the increment of the EMG RMS during the muscle fatigue conditions which cause to increase the EMG-based torque estimation. However, it can be observed from the results in Fig.4 (b) that the robot motion with proposed fuzzy rule based scheme has been able to compensate this effect so that the average peak angle difference between desired and the robot motion for subject A, B and C with this sample 10 [s] periods of Fig.4 (b) are 4 [deg], 8 [deg] and 3 [deg], respectively. Even though a customized fuzzy rule based scheme for each user sees as a limitation, these results suggest its effectiveness on the EMG-based control in muscle fatigue situations. Therefore the proposed method can be applied to compensate the effects of muscle fatigue on EMG-based control.

IV. CONCLUSION

In this paper, a fuzzy rule based scheme has been proposed to compensate for the effects of muscle fatigue on EMG based control. Fuzzy rule based weights have been estimated based on EMG RMS and MPF features of the EMG signals. Those weights have been used to modify the EMG-based torque output according to the muscle fatigue condition of the muscles. The experimental results verified the effectiveness and suggested that this method can be used in EMG-based control to compensate the effects of muscle fatigue conditions.

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