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EMG-Based Neuro-Fuzzy Control of a 4DOF Upper-Limb Power-Assist Exoskeleton

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Abstract—**We have been developing a 4DOF exoskeleton robot system in order to assist shoulder vertical motion, shoulder horizontal motion, elbow motion, and forearm motion of physically weak persons such as elderly, injured, or disabled persons. The robot is directly attached to a user's body and activated based on EMG (Electromyogram) signals of the user's muscles, since the EMG signals directly reflect the user's motion intention. A neuro-fuzzy controller has been applied to control the exoskeleton robot system. In this paper, controller adaptation method to user's EMG signals is proposed. A motion indicator is introduced to indicate the motion intention of the user for the controller adaptation. The experimental results show the effectiveness of the proposed method.**

I. Introduction

ROBOTICS technology is expected to play an important role not only in industries, but also in many other field such as welfare and medicine. Many exoskeleton robots [1]-[13] have been studied to assist daily activity or rehabilitation of physically weak persons such as elderly, injured, or disabled persons. We have been developing a 4DOF exoskeleton robot system in order to assist shoulder vertical motion, shoulder horizontal motion, elbow motion, and forearm motion of physically weak persons such as elderly, injured, or disabled persons, since upper-limb motion is very important for daily activities.

It is important that power-assist exoskeleton robot automatically assist the user's motion according to the user's motion intention. Electromyogram (EMG) is one of the most important biological signals to express the motion intention of the user. The amount of activity level of the skin surface EMG signal reflects the amount of the generating force of the muscles adjacent to the measuring point. Therefore, it is often applied as input information for a controller of some robot systems [14][15] in order to control the robot systems according to the user's intention without any driving equipments. That is especially effective for the power-assist exoskeleton robot to be automatically controlled in accordance with the user's motion intention. However, the EMG-based control is not very easy to be realized for multi-DOF power-assist exoskeletons because 1: obtaining the same EMG signals for the same motion is difficult even with the same person, 2: activity level of each muscle and the way of using each muscle for a certain motion is different between persons, 3: real time motion prediction is not easy since many muscles are involved in a joint motion, 4: one muscle is not only concerned with one motion but also another kinds of motion, 5: role of each muscle for a certain motion varies in accordance with joint angles, and 6: the activity level of some muscles such as bi-articular muscles are affected by the motion of the other joint. Neuro-fuzzy controller is one of the most effective controllers to cope with above mentioned problems [1]-[5].

In this paper, controller adaptation method to user's EMG signals is proposed for the EMG-based neuro-fuzzy controllers of the 4DOF exoskeleton robot. The motion indicator required for controller adaptation is developed. The experimental results show the effectiveness of the proposed method.

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II. 4DOF Upper-Limb Power-Assist Exoskeleton

A power-assist exoskeleton robot that assist 4DOF (shoulder vertical flexion/extension, shoulder horizontal flexion/extension, elbow flexion/extension, and forearm pronation/supination) motion [16] is depicted in Fig. 1. The exoskeleton robot is installed on a mobile wheel chair since many physically weak persons use it, so that the user does not directly support the weight of the exoskeleton robot at all.

It mainly consists of a shoulder motion support part, an elbow motion support part, a forearm motion support part, and a mobile wheel chair. The shoulder motion support part consists of an upper arm link, driver and driven pulleys (one for shoulder horizontal flexion/extension motion, another one for shoulder vertical flexion/extension motion), two DC motors, two potentiometers, an arm holder, and the mechanism of moving centre of rotation (CR) of shoulder joint. The 1DOF elbow motion assist part consists of a forearm link, pulleys, a DC motor, and a potentiometer. The forearm motion support part consists of a wrist frame, an inner and an outer wrist holder, a wrist cover, a wrist force sensor, and potentiometers. The wrist force sensor measures the force caused from the motion difference between the user's hand and the wrist holder of the exoskeleton.

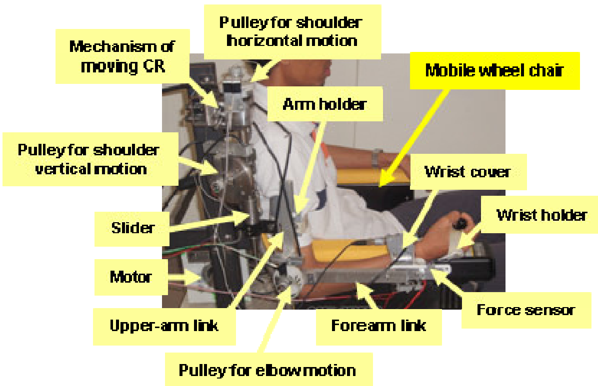

Fig. 1. 4DOF upper-limb power-assist exoskeleton.

The movable range of the shoulder motion of the 4DOF exoskeleton is limited to 0º in extension and adduction, 90º in flexion, and 90º in abduction. The movable range of its forearm motion is limited to be 50º in pronation and 80º in supination, and that of elbow motion is limitted to be 120º in flexion and 0º in extension.

III. Control of Exoskeleton

The EMG signals of the related muscles are used as main control inputs for the exoskeleton robot to be controlled in accordance with motion intention of the user. In order to predict the 4DOF motion (shoulder vertical flexion/extension, shoulder horizontal flexion/extension, elbow flexion/extension, and forearm supination/pronation), the EMG signals of 12 locations (Deltoid – anterior part, Deltoid – posterior part, Pectoralis Major – clavicular part, Teres Major, Biceps – short head, Bicesp – long head, Triceps – long head, Triceps – lateral head, Pronator Teres, Flexor Carpi Radialis, Anconeus, and Extensor Carpi Radialis Longus) of the related muscles are measured and analyzed in the intelligent controller. The location of each electrode is depicted in Fig. 2. Since the raw EMG signal is difficult to be used as input information for the controller, the root mean square (RMS) is calculated to extract the feature of the signal.

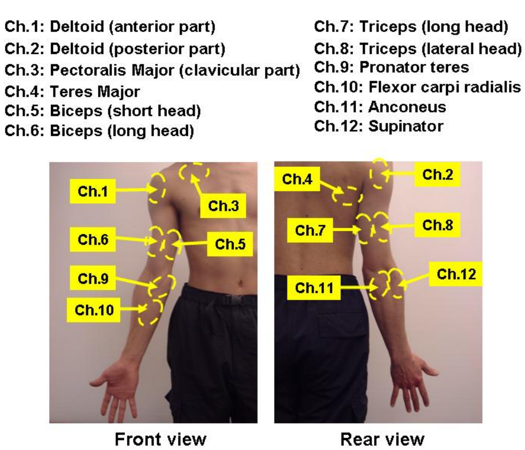

Fig. 2. Location of each electrode.

The equation of RMS is written as:

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N} v_i^2} \tag{1}$$

where, v_i is the voltage value at the i^{th} sampling and N is the number of sample in a segment. The number of sample is set to be 100 and the sampling time is 500μsec in this study.

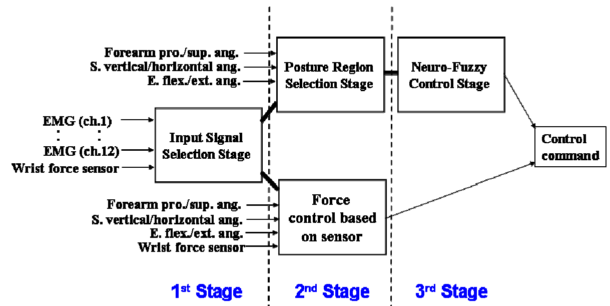

Fig. 3. Controller architecture.

The basic architecture of the controller is depicted in Fig. 3. The controller basically consists of three stages (first stage: input signal selection stage, second stage: posture region selection stage, and third stage: neuro-fuzzy control stage). In the first stage of the controller, the EMG based control or the wrist sensor based control is applied in accordance with the muscle activity levels of the user. In the second stage of the controller, a proper neuro-fuzzy controller is selected according to the shoulder and the elbow angle region. In the third stage of the controller, the desired torque command for each joint is calculated with the selected neuro-fuzzy controllers to realize 4DOF upper-limb power-assist for the user.

In the first stage of the controller, proper control (the EMG-based control or the wrist force sensor based control) is selected in accordance with the user's muscle activity levels. If the activity level of every muscle is little, the wrist sensor based control is selected in this stage in order to avoid misoperation. When the user activates his/her muscles, the EMG-based control is selected. These control methods are gradually switched according to the user's muscle activity levels.

The movable range of the elbow flexion/extension, the shoulder vertical flexion/extension, and the shoulder horizontal flexion/extension is divided into three regions (flexed region, intermediate region, and extended region), respectively. The regions, in which the current upper-limb posture involved in, are evaluated in the second stage of the controller. Appropriate neuro-fuzzy controller has been prepared for each region, since the EMG-based control rules are sometimes different when the upper-limb posture is changed because the role of each muscle is changed according to the upper-limb posture.

Selected neuro-fuzzy controllers are used to generate the desired torque command for the power-assist in the third stage of the controller.

IV. Controller Adaptation

If physical or physiological condition of the user is changed, EMG signals for the same motion are changed even with the same person. Furthermore, activity level of each muscle and the way of using each muscle for a certain motion is different if the user is changed. Therefore, the neuro-fuzzy controller (i.e., the third stage of the controller) of the exoskeleton has to adapt itself to the user's EMG levels. In this study, the error back-propagation learning algorithm is applied to minimize the amount of the evaluation function for the adjustment of the neuro-fuzzy controller. In order to indicate the user's motion intention correctly, a motion indicator (Fig. 4) that has the same degree of freedom with the same link ratio and directly operated by the user's hand of the other arm (i.e., not assisted arm). The user is supposed to indicate with the motion indicator how the assisted upper-limb is moving (i.e., the correct motion intention of the user).

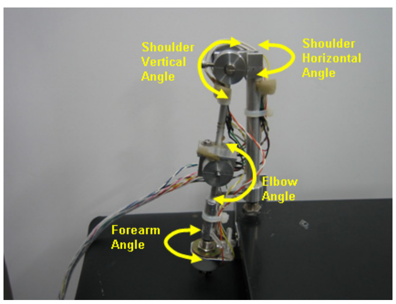

Fig. 4. Motion indicator.

The evaluation function for the controller adjustment is defined as:

$$E = \frac{1}{2}((\theta_d - \theta)^2 + \alpha \sum (RMS_d - RMS)^2) \qquad (2)$$

where θ_d is the desired joint angle indicated by the motion indicator (teaching equipment) shown in Fig. 4, θ is the joint angle of the exoskeleton, α is a learning rate, and RMS_d is the desired EMG level. When the joint angle error is little, the neuro-fuzzy controller is not adjusted.

The controller adjustment is supposed to be performed for a few minute when the user is changed or the physiological condition of the user is changed.

V. Experiment

In order to evaluate the effectiveness of the proposed adaptation method, experiment has been carried out with and without adaptation.

In the fist experiment, each joint motion is evaluated with three healthy young male subjects. In this experiment, the controller adaptation is performed for 45 seconds for each joint motion. The experimental results (ch.1: Deltoid – anterior part) of shoulder vertical flexion motion of the subject A and B are shown in Fig. 5 and Fig. 6, respectively. In the case of the subject A, shoulder vertical flexion motion could not be generated properly before learning even though the muscle was activated very much since the controller did not fit to the user's condition. On the other hand, shoulder vertical flexion motion was properly generated with less muscle activity after learning since the controller was adjusted to fit to the user's condition. In the case of the subject B, shoulder vertical flexion motion was properly generated in before and after learning. However, the activity level of the muscle for the same motion is reduced after learning.

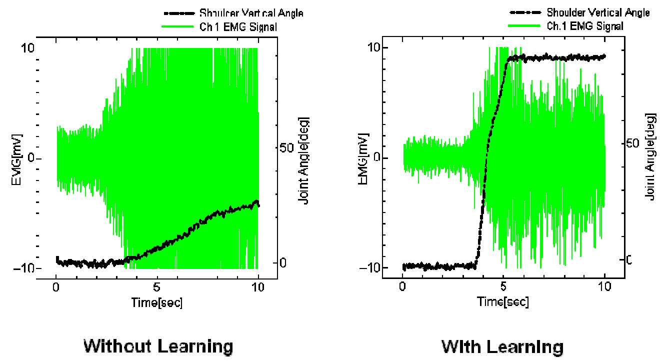

Fig. 5. Experimental results of shoulder vertical flexion motion (subject A).

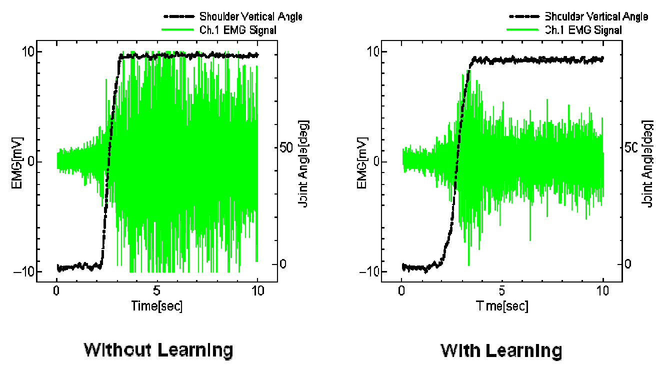

Fig. 6. Experimental results of shoulder vertical flexion motion (subject B).

The experimental results (ch.5: Biceps – short head) of elbow flexion motion of the subject A and B are shown in Fig. 7 and Fig. 8, respectively. In both cases, shoulder vertical flexion motion could not be generated properly before learning even though the muscle was activated very much since the controller did not fit to the user's condition. On the other hand, shoulder vertical flexion motion was properly generated with less muscle activity after learning since the controller was adjusted to fit to the user's condition.

In the second experiment, 4DOF cooperative motion (i.e., cooperative of shoulder vertical/horizontal motion, elbow motion, and forearm motion) is evaluated with a healthy young male subject. The experimental results (ch.5: Biceps – short head, and ch.7: Triceps – long head) of 4DOF cooperative motion are shown in Fig. 9 and Fig. 10, respectively. These results show that the controller was adjusted to fit to the user's condition since the amount of the muscle activity levels were reduced for the similar motion.

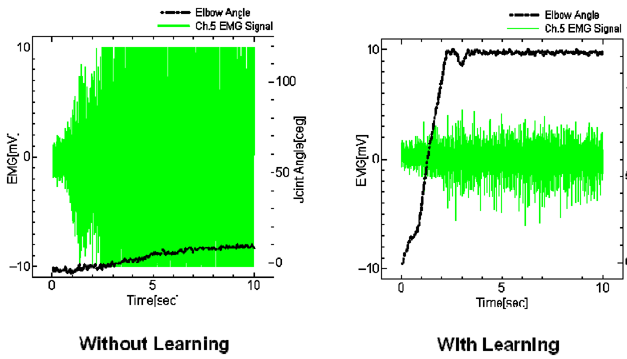

Fig. 7. Experimental results of elbow flexion motion (subject A).

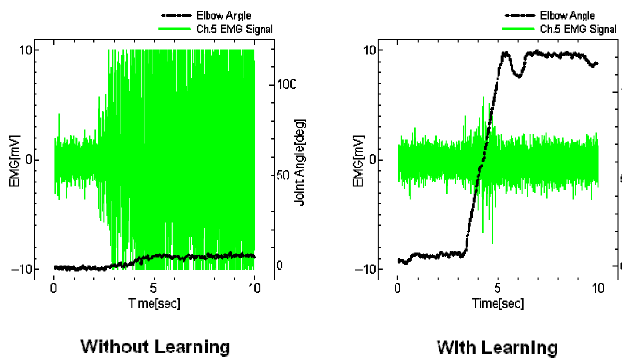

Fig. 8. Experimental results of elbow flexion motion (subject B).

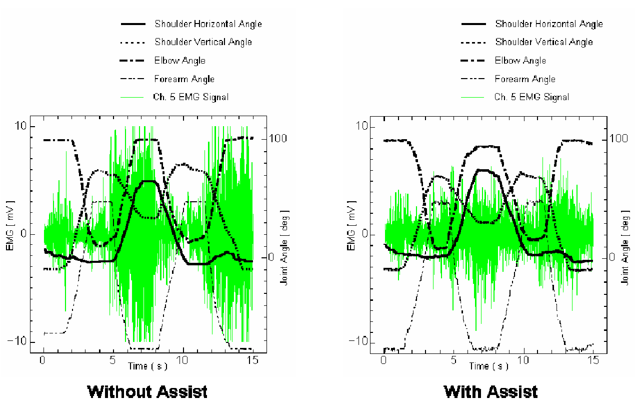

Fig. 9. Experimental results of 4DOF cooperative motion (ch.5).

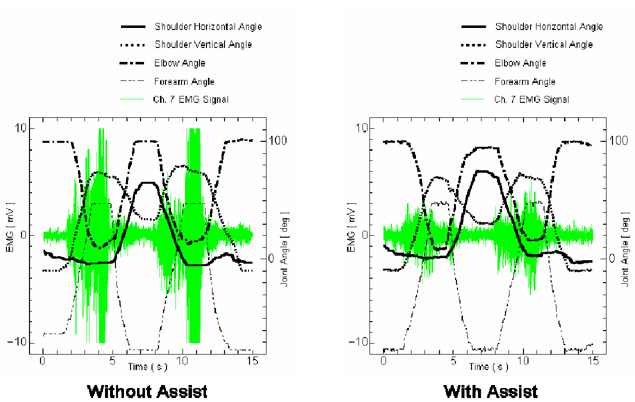

Fig. 10. Experimental results of 4DOF cooperative motion (ch.7).

VI. Conclusion

A controller adaptation method is proposed to make the EMG-based neuro-fuzzy controllers of the 4DOF exoskeleton robot adapt itself to each user. The experimental results showed the effectiveness of the proposed controller adaptation method.

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