

Application of Multiple Fuzzy-Neuro Controllers of an Exoskeletal Robot for Human Elbow Motion Support

Kazuo Kiguchi, Shingo Kariya, Keigo Watanabe, and Toshio Fukuda

Abstract: A decrease in the birthrate and aging are progressing in Japan and several countries. In that society, it is important that physically weak persons such as elderly persons are able to take care of themselves. We have been developing exoskeletal robots for human (especially for physically weak persons) motion support. In this study, the controller controls the angular position and impedance of the exoskeletal robot system using multiple fuzzy-neuro controllers based on biological signals that reflect the human subject's intention. Skin surface electromyogram (EMG) signals and the generated wrist force by the human subject during the elbow motion have been used as input information of the controller. Since the activation level of working muscles tends to vary in accordance with the flexion angle of elbow, multiple fuzzy-neuro controllers are applied in the proposed method. The multiple fuzzy-neuro controllers are moderately switched in accordance with the elbow flexion angle. Because of the adaptation ability of the fuzzy-neuro controllers, the exoskeletal robot is flexible enough to deal with biological signal such as EMG. The experimental results show the effectiveness of the proposed controller.

Keywords: exoskeletal robot, fuzzy-neuro control, multiple controller, power assist, human elbow motion

I. Introduction

A decrease in the birthrate and aging are progressing in Japan and several countries. In that society, it is important that physically weak people such as elderly people are able to take care of themselves. Recent progress of robotics technology has brought a lot of benefits not only in the industries, but also in many other fields such as welfare, medicine, or amusement. Using such robotics technology, we have been developing exoskeletal robots for human (especially for physically weak people) motion support in everyday life [1][2]. Since the robot is supposed to be used for everyday life of human subjects in living space, its motion has to be flexible enough. Furthermore, subject's intention has to be directly reflected to the robot movement. Unlike previously proposed another exoskeletal robots [3]-[8], the proposed exoskeletal robot in this study is supposed to generate flexible human-like motion based on biological signals that directly reflect the subject's intention. In this paper, we propose an effective control method for a 1DOF exoskeletal robot to support the human elbow motion. The proposed controller controls the angular position and impedance of the exoskeletal robot system using multiple fuzzy-neuro controllers based on biological signals that reflect the human subject's intention. Skin surface electromyogram (EMG) signals, which are important biological information to understand the subject's muscle activities, and the generated wrist force by the human subject (i.e., the force caused from the motion difference between the exoskeletal robot and the human subject) during the elbow motion have been used as input information of the controller. A DC motor has been applied to actuate the exoskeletal robot.

Since the activation level of working muscles tends to vary

in accordance with the flexion angle of elbow because of physiological reason [9][10] although the same muscles are activated for elbow motion, multiple fuzzy-neuro controllers are applied in the proposed method. The multiple fuzzy-neuro controllers are moderately switched in accordance with the elbow flexion angle by applying the membership functions for the elbow flexion levels. Because of the adaptation ability of the fuzzy-neuro controllers, the exoskeletal robot is flexible enough to deal with vague biological signal such as EMG. The experimental results show the effectiveness of the proposed controller.

II. Exoskeletal robot system

We have designed the 1DOF exoskeletal robot for human elbow motion support. This exoskeletal robot is supposed to be attached directly to the lateral side of a human arm as shown in Fig. 1. This robot consists of two links, a ballscrew drive shaft, a ballscrew support frame, a DC motor [RH14C-3002-E1000D0, Harmonic Drive System Co.], and force sensors (strain gauges). The DC motor drives the ballscrew drive shaft to make the link-2 flex or extend. The link-2 is flexed (or extended) by contracting (or expanding) the prismatic joint along the ballscrew drive shaft in the ballscrew support frame, which is attached to the link-1, as shown in Fig. 2. The generated wrist force (i.e., the force caused from the motion difference between the exoskeletal robot and the human subject) during the human elbow motion is measured by the strain gauge based force sensor. In this force sensor, strain gauges are attached on the beams between the wrist holder outer cover, which is connected to the exoskeletal robot, and the wrist holder inner cover, which is connected to the human subject (Fig. 3). The signal from the force sensor is sampled at a rate of 2kHz and low-pass filtered at 4Hz. The measured force by these force sensors are used to understand the force externally acting on the human subject's forearm.

The skin surface EMG signals of biceps and triceps, which imply the human subject's intention, are used as another input information to control the exoskeletal robot. The electrodes are located on the medial and lateral side of biceps and those

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on the lateral and medial side of triceps, and connected to ch.1, ch.2, ch.3, and ch.4, respectively. The details of the method of control with these signals are explained in Section 4.

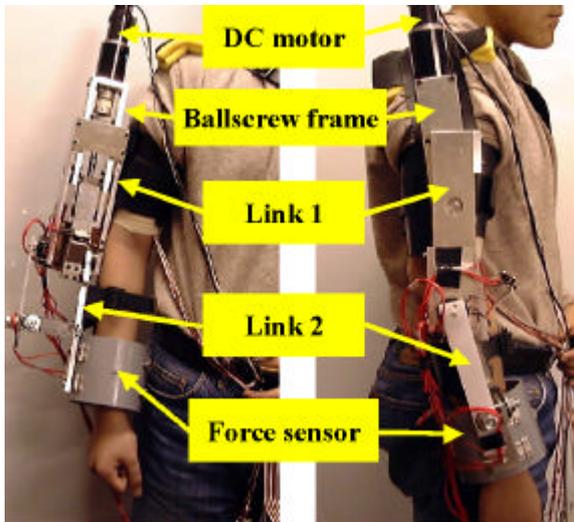


Fig. 1. The attached exoskeletal robot.

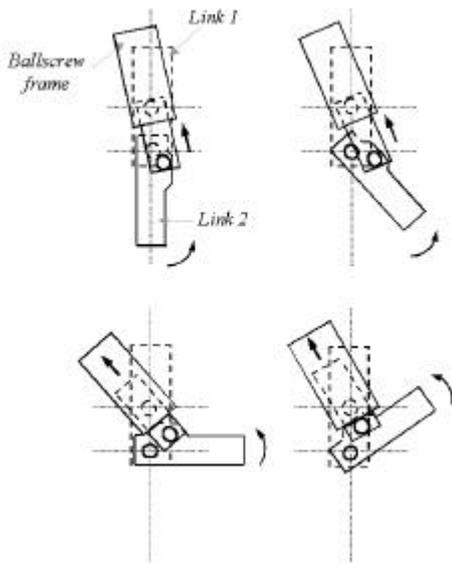


Fig. 2. Generation of flexion motion of the robot.

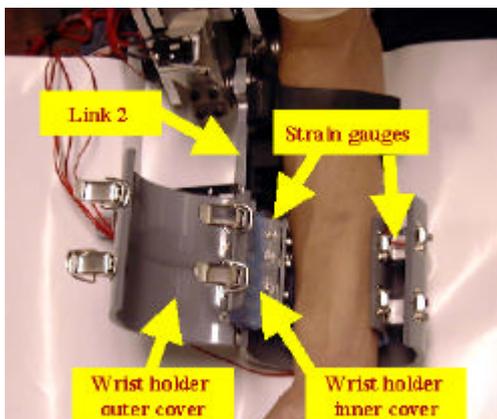


Fig. 3. The strain gauge based force sensor.

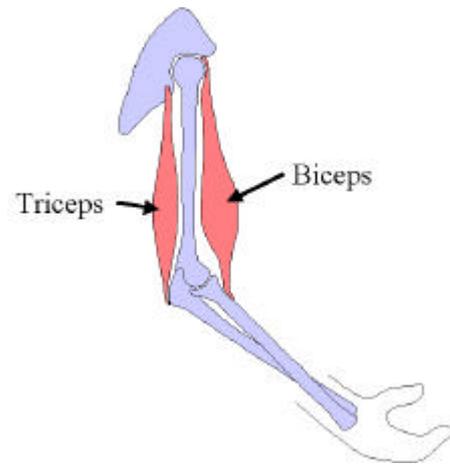
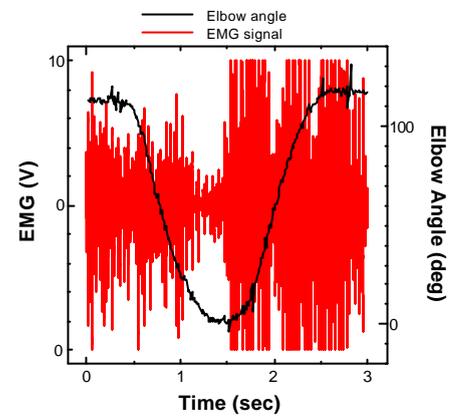
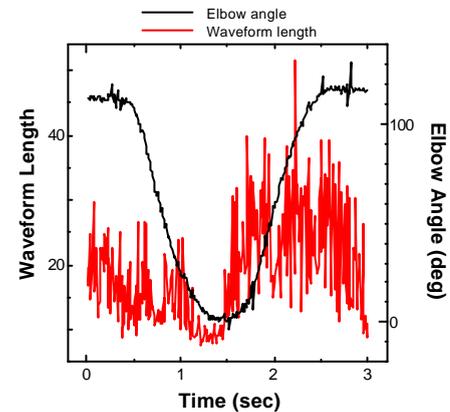


Fig. 4. Human arm.



(a)EMG.



(b)waveform length (WL) of EMG.

Fig. 5. Sample of WL and EMG during elbow motion.

III. Human elbow motion

Agonist-antagonist muscles exist in many human joint such as elbow, knee, wrist, ankle, etc.. Such human joint is usually activated by many muscles. Human elbow is mainly actuated by two antagonist muscles: biceps and triceps, although it consists of more muscles. The effect of those muscle force to the elbow joint torque varies as a function of the elbow joint angle because of physiological reason. The physiological layout of those muscles is depicted in Fig. 4. By adjusting the amount of force generated by these muscles, the elbow angle

and impedance can be arbitrary controlled [11]. The muscle activity level can be described by the EMG signal. The amplified EMG signals are sampled at a rate of 2kHz. Since it is difficult to use raw data of EMG for input information of the controller, features have to be extracted from the raw EMG data. There are many kinds of feature extraction methods, e.g., Mean Absolute Value, Mean Absolute Value Slope, Zero Crossings, Slope Sign Changes, or Waveform Length [12]. We have tested all these feature extraction methods, and found out that Waveform Length (WL) is the most suitable feature to express the EMG levels for the fuzzy-neuro control. This is the cumulative length of the waveform over the time segment. The equation of WL is written as:

$$WL = \sum_{k=1}^N |x_k - x_{k-1}| \quad (1)$$

where x_k is the k th sample voltage value and N is the number of samples in segment. The number of samples is set to be 100 in this study. An example of the WL of biceps obtained in the pre-experiment is shown in Fig. 5. One can see that the biceps are activated during the elbow flexion motion from the magnitude of the WL.

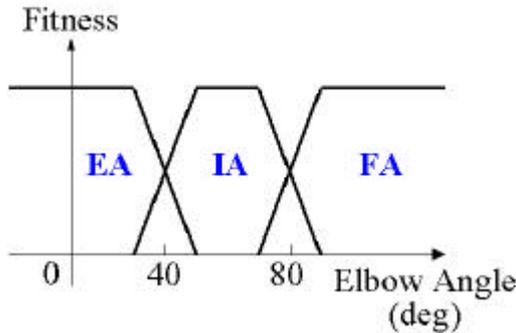


Fig. 6. Membership functions for elbow flexion angle.

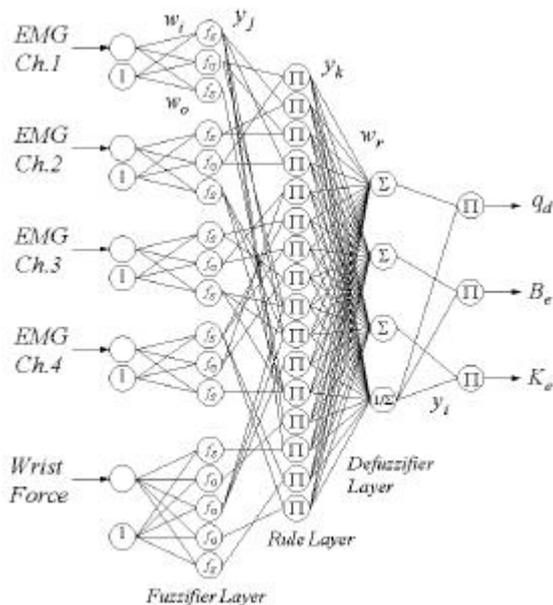


Fig. 7. Architecture of the fuzzy-neuro controller.

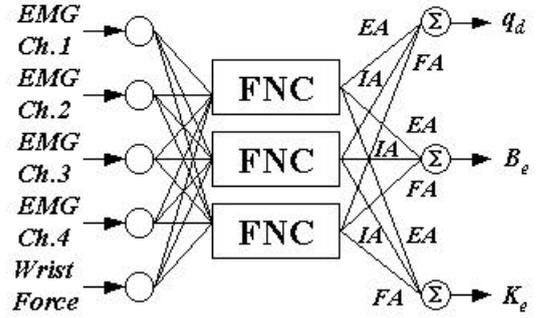


Fig. 8. Structure of the proposed controller.

IV. Control of the exoskeletal robot

The movable range of elbow is divided into three sections (i.e., EA: Extended Angle, FA: Flexed Angle, and IA: Intermediate Angle) and expressed by membership functions as shown in Fig. 6. A fuzzy-neuro controller (Fig. 7) is designed for each section. Therefore, three fuzzy-neuro controllers are prepared in total and moderately switched according to the elbow flexion angle using fuzzy reasoning to control the exoskeletal robot. The fuzzy-neuro controllers are supposed to control both the angle and impedance of the exoskeletal robot based on both the skin surface EMG signals of biceps and triceps and the generated wrist force. So that the robot can be controlled in accordance with the human subject's intention. The structure of the controller is depicted in Fig. 8. The fuzzy IF-THEN control rules of the fuzzy-neuro control are designed based on the analyzed human subject's elbow motion patterns in the pre-experiment and the properties of human elbow impedance studied in another research [13]. By applying sensor fusion with the skin surface EMG signals and the generated wrist force, error motion caused by little EMG levels and the external force affecting to human arm can be avoided.

The input variables of the fuzzy-neuro control are the WL of biceps (2 channels) and triceps (2 channels) and the generated wrist force measured by the wrist force sensor. Three kinds of fuzzy linguistic variables (ZO: zero, PS: positive small, and PB: positive big) are prepared for the WL of EMG and five kinds of fuzzy linguistic variables (NB: negative big, NS: negative small, ZO: zero, PS: positive small, and PB: positive big) are prepared for the generated wrist force data. The outputs of the fuzzy-neuro control are the desired joint angle and impedance of the exoskeletal robot. In this method, impedance control is performed to follow the generated desired joint angle using the generated desired impedance coefficients. Consequently, both the angle and impedance of the exoskeletal robot are controlled like human beings. The equation of impedance control is written as:

$$\mathbf{t}_e = M_e(\ddot{q}_d - \ddot{q}) + B_e(\dot{q}_d - \dot{q}) + K_e(q_d - q) \quad (2)$$

where \mathbf{t}_e denotes torque command for the exoskeletal robot joint, M_e is the moment of inertia of link 2 and human subject's forearm, B_e is the viscous coefficient generated by the fuzzy-neuro controller, K_e is the spring coefficient generated by the fuzzy-neuro controller, q_d is the desired joint angle

generated by the fuzzy-neuro controller, and q is the measured joint angle of the exoskeletal robot. The torque command for the exoskeletal robot joint is then transferred to the torque command for the driving motor. In each fuzzy-neuro controller, 16 kinds of fuzzy IF-THEN rules are prepared to generate the desired joint angle and impedance of the exoskeletal robot.

The fuzzy-neuro controller is able to adapt itself to physiological condition of each human subject on-line. In this study, the antecedent part and some of the consequence part (i.e. fuzzy rules for the desired joint angle generation) of the fuzzy IF-THEN control rules are supposed to be adjusted. The back-propagation learning algorithm has been applied to minimize the squared error function written below.

$$E = \frac{1}{2}(q_d - q)^2 \quad (3)$$

where q_d is the angle of the desired motion and q is the measured joint angle of the exoskeletal robot. The desired motion of the exoskeletal robot, which is required for the evaluation function of the back-propagation learning, is demonstrated by the teaching equipment attached on the other arm of the subject. The subjects are supposed to generate the same elbow motion in both arms during the teaching time.

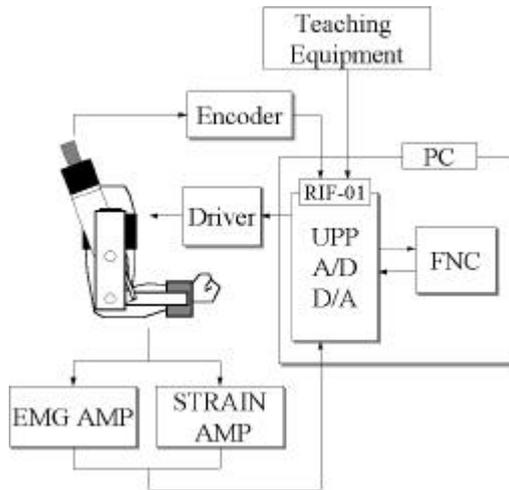
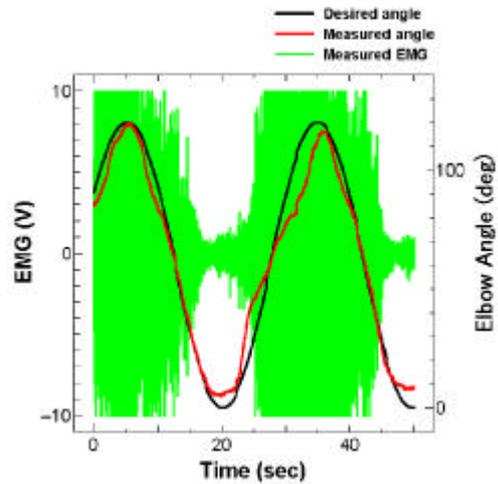


Fig. 9. Experimental setup.

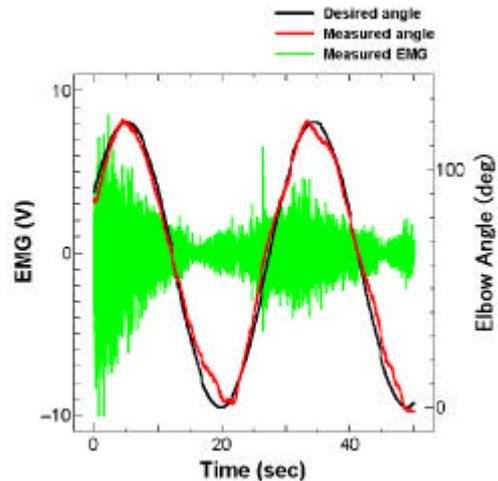
V. Experiment

In order to evaluate the proposed control method, the target following experiments have been carried out with and without support of the exoskeletal robot in order to evaluate the accuracy of the system. Figure 9 shows the experimental setup. In this experiment, the healthy human male subject A (24 years old) is supposed to make his elbow flexion angle follow the target trajectory shown on the display with a heavy weight (7kg) in his hand. The target flexion angle of the elbow angle is given as sinusoidal trajectory: $60\sin(0.2t)$ [deg]. Since the human subject try to adjust his elbow flexion angle to follow the target trajectory shown on the display, a little motion error is inevitable. Figure 10 shows the experimental result of the target following with and without support of the exoskeletal robot. Since the biceps are supposed to be the most active

muscle during this experiment, only the EMG signal of ch.1 (medial side of biceps) is depicted. The EMG levels of biceps during the heavy weight manipulation are supposed to be lower if the proposed exoskeletal robot supports the human motion properly. Comparing the results in Fig. 10(a) and 10(b), one can see that the EMG levels of biceps during the target following motion with the heavy weight in his hand are much lower when the elbow motion is supported by the exoskeletal robot. One can see that nice target following result with support of the exoskeletal robot has been recorded. This result shows the effectiveness of the controllability of the exoskeletal robot.



(a) without support of the exoskeletal robot.



(b) with support of the exoskeletal robot.

Fig. 10. Experimental result with the exoskeletal robot(subject A).

In the case when only one fuzzy-neuro controller is applied for the control of whole movable range of the exoskeletal robot, the controllability sometimes become worse especially in the extended angle as shown in Fig. 11.

Next, the same experiments have been performed by another healthy human subjects B (23 years old) and C (24 years old) in order to evaluate the adaptation ability of the proposed controller. Figure 12 and 13 show the experimental results of the subject B and C, respectively. One can see that the exoskeletal robot

has effectively supported the elbow motion of another subjects. So that the adaptation ability of the exoskeletal robot system has been verified from these experimental results.

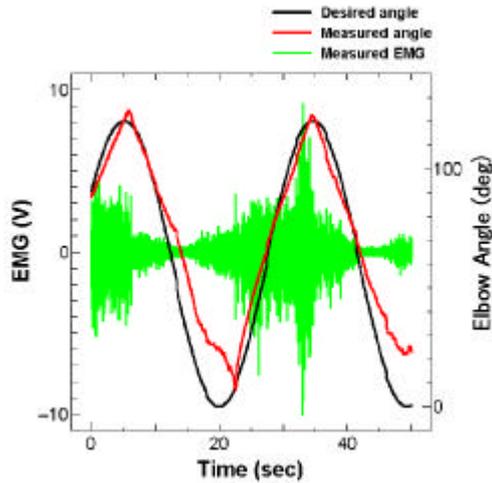
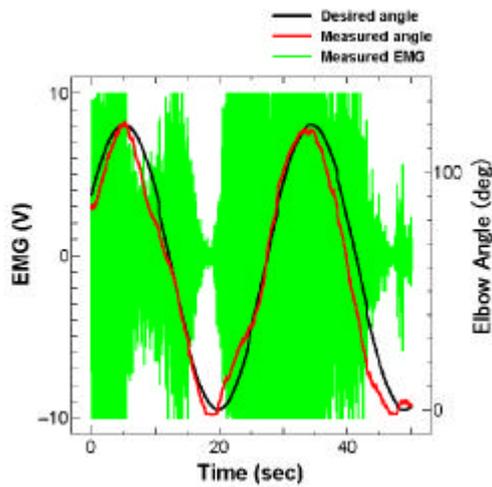
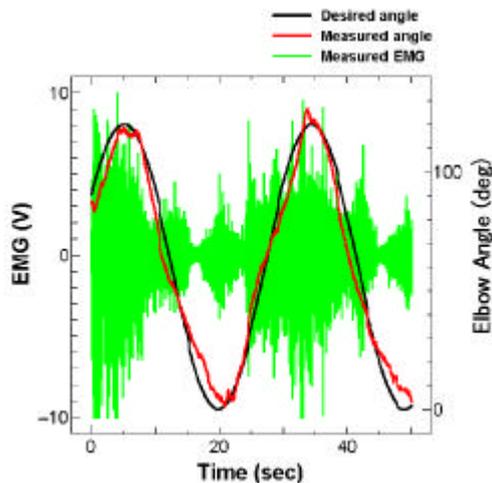


Fig. 11. Example of poor experimental result with one fuzzy-neuro controller (subject A).

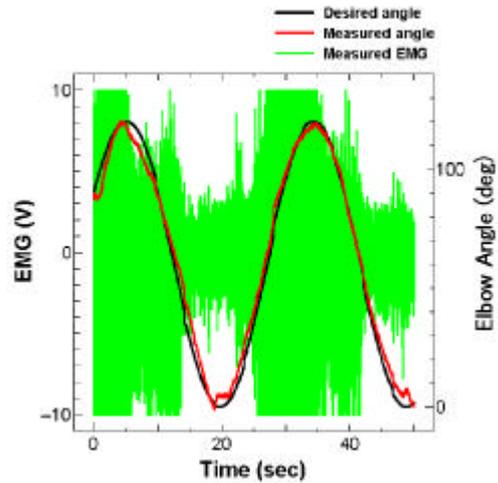


(a)without support of the exoskeletal robot.

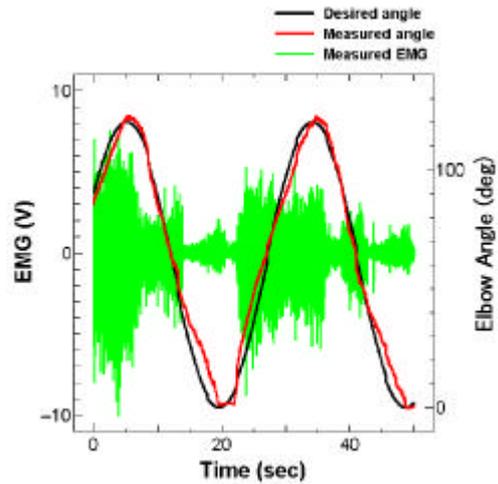


(b)with support of the exoskeletal robot.

Fig. 12. Experimental result with the exoskeletal robot (subject B).



(a)without support of the exoskeletal robot.



(b)with support of the exoskeletal robot.

Fig. 13. Experimental result with the exoskeletal robot (subject C).

VI. Conclusion

Multiple fuzzy-neuro controllers are applied to effectively control the exoskeletal robot for human elbow motion support in any elbow angle. The controllers are moderately switched according to the elbow angle using fuzzy reasoning. The reliability and the smoothness of the generated motion with support of the exoskeletal robot have been improved by applying the proposed control method. The experimental results have been performed to verify the effectiveness in motion support and adaptation of the proposed exoskeletal robot system.

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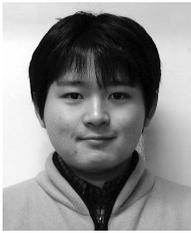


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