Proceedings of the 2004 IEEE
International Conference on Robotics & Automation
New Orleans, LA • April 2004

A 3DOF Exoskeleton for Upper-Limb Motion Assist - Consideration of the Effect of Bi-Articular Muscles

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Abstract - **We have been developing exoskeleton systems to assist the motion of physically weak persons such as elderly, disabled, and injured persons. The proposed exoskeletons are controlled basically based on the electromyogram (EMG) signals. Even though the EMG signals contain very important information, however, it is not very easy to predict the user's upper-limb motion (elbow and shoulder motion) based on the EMG signals in real-time because of the difficulty in using the EMG signals as the controller input signals. In this paper, we propose a control method for a 3DOF exoskeleton system for human upper-limb motion assist considering the effect of bi-articular muscles.**

Index Terms - power assist; biorobotics; neuro-fuzzy control; EMG; human motion.

I. INTRODUCTION

We have been developing exoskeleton systems [1]-[4] to assist motion of physically weak persons such as elderly, disabled, and injured persons. These kinds of robotic systems can be used for power assist of physically weak persons in daily activity and rehabilitation. It is important for the exoskeleton, especially that for medical or welfare use, to be controlled according to the user's intention. The skin surface electromyogram (EMG) is one of the most important biological signals in which the human motion intention is directly reflected. Therefore, it is often used as a control command signal for a robot system [5]-[7]. In this paper, a control method for a 3DOF exoskeleton system for human upper-limb motion (elbow flexion/extension motion, and shoulder vertical/horizontal flexion/extension motion) assist, which is mainly controlled based on the EMG signals, is proposed considering the effect of bi-articular muscles.

It is very difficult to obtain the same EMG signals for the same motion even with the same person, although the EMG signals are very important information for the exoskeleton system. Furthermore, each muscle activity for a certain motion is highly nonlinear, because the responsibility of each muscle for the motion varies in accordance with joint angles [8][9]. One muscle is not only concerned with one motion but also another kinds of motion. Moreover, activity level of each muscle and the way of using each muscle for a certain motion is different between persons. Physiological condition of the user also affects the activity level of muscles [10]. In addition to these problems, the activity level of some muscles such as bi-articular muscles is affected by the motion of the other joint, because the load acting on the other joint affects the activity level of them. The relationship between the load acting on the other joint and the change in bi-articular muscle activity level is different between persons. Therefore, the effect of the bi-articular muscles is taken into account in the controller of the EMG-based controlled exoskeleton system.

Since anatomy and the way of muscle use of each person are basically similar, design of basic initial fuzzy IF-THEN control rules for the exoskeleton is not too difficult. However, since activity level of each muscle and the way of using each muscle for a certain motion is different between persons, the controller must be adjusted based on physical and physiological condition of each user. Therefore, the required structure of the neuro-fuzzy (control rules) is sometimes different between persons. In this paper, we propose a flexible neuro-fuzzy controller of the 3DOF exoskeleton for any user. The structure of the proposed neuro-fuzzy controller is basically the same as the conventional simplified fuzzy controller. So that the weight of the consequent part of the most control rules is singleton. However, the weight of the consequent part of some control rules in the proposed controller is described by equation in order to take into account the activity of bi-articular muscles used for the other joint. In this point, the controller is similar to the Takagi-Sugeno-Kang (TSK) model [11]-[14]. Unlike the traditional TSK model where all the input variables are used in the equation of the consequent part, only the related EMG signals are used in the proposed method. Thus, the main-effect of each muscle is taken into account in the antecedent part of the controller and the sub-effect of some muscles is taken into account in the consequent part of the controller. If there is no sub-effect from the other muscles, the neuro-fuzzy controller is the same as the simplified neuro-fuzzy controller.

II. EXOSKELETON

The 3DOF exoskeleton is supposed to be attached directly to the lateral side of a user. The architecture of the exoskeleton system is shown in Fig. 1. The exoskeleton system consists of four main links (two links for shoulder joint motion and another two links for elbow joint motion), a frame, three DC motors, an upper-arm holder, a wrist force sensor, driving wires, wire tension sensors, and driving motors. An air cushion is attached inside of the upper arm holder. By adjusting the air pressure of the air cushion, the upper arm holder can be properly attached to the upper arm of any user. The shoulder vertical and horizontal flexion-extension of the user (see Fig. 2) are assisted by the exoskeleton system by activating the upper arm holder, which is attached on the main link-2 for shoulder

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joint motion, using driving wires driven by two DC motors. Since the center of rotation of the exoskeleton's shoulder joint is different from that of human shoulder joint, the radius of rotational joint is adjusted in accordance with the joint motion [2]. The shoulder angle is measured by potentiometers attached to the link-1 and link-2 of the exoskeleton. The wire tension (driving force) is measured by the wire tension sensors. The signals from the sensors are sampled at a rate of 2kHz (the EMG signals are also sampled at the same time) and low-pass filtered at 8Hz.

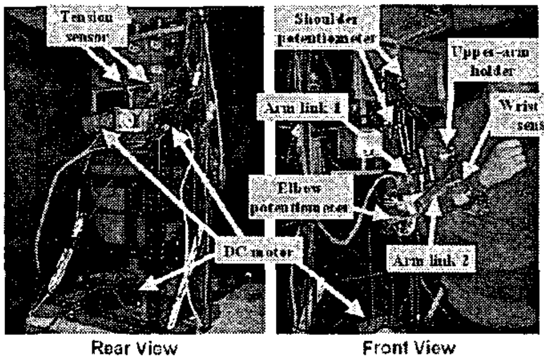


Figure 1. 3DOF exoskeleton for upper-limb motion assist.

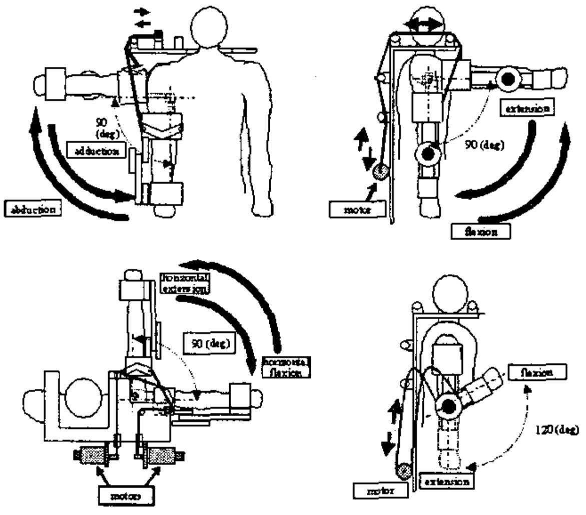


Figure 2. Movement of exoskeleton.

The elbow flexion-extension motion of the user (see Fig. 2) is assisted by the exoskeleton system by activating the elbow joint pulley using the driving wire. In order to make the movable links light weight, DC motors are fixed on the frame.

Usually, the limitation of the movable range of human elbow is between -5 and 145 degrees and that of human shoulder are 180 degrees in flexion, 60 degrees in extension, 180 degrees in abduction, and 75 degrees in adduction. Considering the minimally required motion in everyday life and the safety of the parient, the elbow joint motion of the proposed exoskeleton system is limited between 0 and 120 degrees, and the limitation of the shoulder joint motion of the proposed exoskeleton system are decided to be 0 degrees in extension and adduction, 90 degrees in flexion, and 90 degrees in abduction.

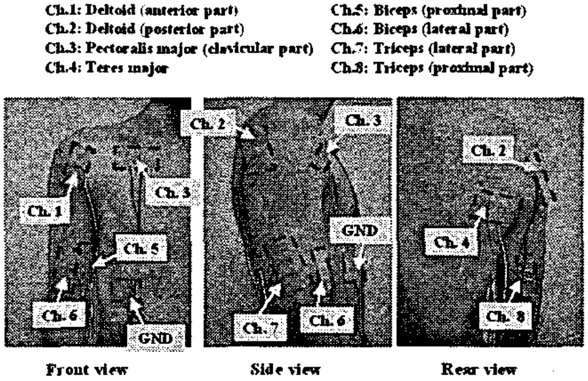


Figure 3. Location of electrode.

III. CONTROLLER

The proposed controller 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 proposed controller, the EMG based control or the wrist sensor based control is applied in accordance with the muscle activity levels of the robot user. In the second stage of the proposed controller, a proper neuro-fuzzy controller is selected according to the shoulder and the elbow angle region. In the third stage of the proposed controller, the desired torque command for each joint is generated by the neuro-fuzzy controllers to realize the effective motion assist for the exoskeleton user.

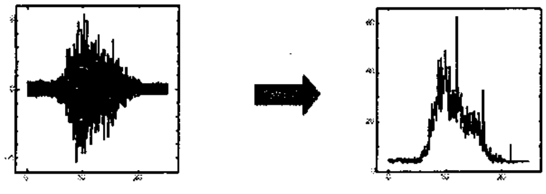
A. EMG Signals

Human elbow joint is mainly activated by biceps and triceps, and moves in 1 DOF. Human shoulder joint is activated by many muscles such as deltoid, pectoralis major, teres major, and trapezius, and moves in 3 DOF. In this study, EMG signals of biceps (lateral and proximal parts), triceps (lateral and proximal parts), deltoid (anterior and posterior parts), pectoralis major (clavicular part), and teres major are measured and used for control of the exoskeleton system. The location of each electrode is shown in Fig. 3.

The EMG signal (0.01-10mV, 10-2,000Hz) is one of the most important biological signals which directly reflect human muscle activities. Since it is difficult to use raw EMG data as input information of the controller, features have to be extracted from the raw EMG data. We have used Mean Absolute Value (MAV) considering its effectiveness for real-time control, although there are many other feature extraction methods, e.g., Mean Absolute Value Slope, Zero Crossings, Slope Sign Changes, or Waveform Length [15]. The equation of MAV is written as:

$$MAV = \frac{1}{N}\sum_{k=1}^{N}|x_k| \tag{1}$$

where x_k is the voltage value at k^{th} sampling, N is the number of samples in a segment. The number of samples is set to be 100 and the sampling time is set to be 1ms in this study. Figure 4 show an example of raw EMG signal and its MAV.



EMG

MAV

Figure 4. Example of EMG and MAV.

B. *Input Signal Selection Stage*

In the first stage of the controller, proper input information for the controller is selected in accordance with the user's muscle activation levels. The control is carried out based on the EMG signals when the robot user is activating his/her shoulder and/or upper-arm muscles. However, when the muscle activity level of the robot user is not so high (i.e., when the exoskeleton user is not activating his/her shoulder and/or upper-arm muscles), the control is carried out based on the wrist force sensor signals in the proposed control method. Consequently, both elbow and shoulder motion is controlled based on the generated wrist force when the activity level of all muscle is low, and only elbow motion is controlled based on the generated wrist force when the activity level of only the upper-arm muscle is low. When the activity level of the muscle is medium, both the skin surface EMG signals and the generated wrist force are used simultaneously for the control. In the case of control based on the generated wrist force, force control is carried out to make the generated wrist force become zero. 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 membership function (PB: Positive Big) of each muscle is used to switch the controller input information. By applying the membership function of each muscle for switching, the input information for the controller is gradually switched in this stage.

C. *Posture Reagion Selection Stage*

In the second stage of the controller, proper neuro-fuzzy controller is selected in accordance with the user's arm posture. The EMG-based control rules are sometimes completely different when the arm posture is changed since role of each muscle is changed according to the arm posture. In order to cope with this problem, multiple neuro-fuzzy controllers have been designed and applied under the certain arm posture. Consequently, the proper neuro-fuzzy controller is selected according to the shoulder and elbow posture region in this stage. The details of each neuro-fuzzy controller are presented in the next sub-section.

The movable range of elbow flexion/extension angle, shoulder vertical flexion/extension angle, and shoulder horizontal flexion/extension angle are divided into three regions (FA: flexed angle, IA: intermediate angle, and EA: extended angle), respectively. Therefore, the movable range of the elbow motion is divided into three regions and that of the shoulder motion is divided into nine regions. By applying these membership functions, the appropriate controllers are moderately selected in accordance with the arm posture of the user. Thus, four kinds of neuro-fuzzy controller might be used at the same time in maximum for shoulder motion and two kinds of neuro-fuzzy controller might be used at the same time in maximum for elbow motion.

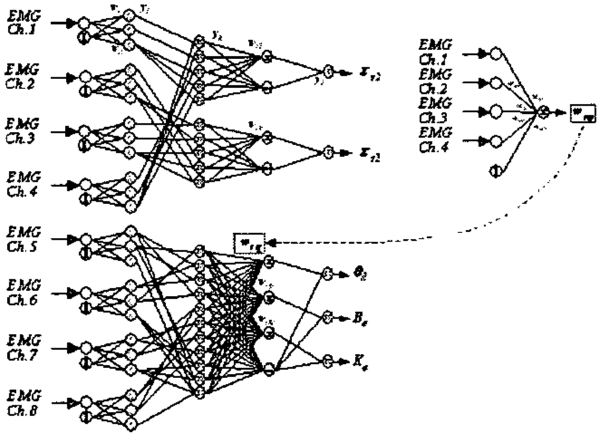


Figure 5. Neuro-fuzzy controller.

D. *Neuro-Fuzzy Control Stage*

The desired torque command for each joint is derived by the neuro-fuzzy control in the third stage of the controller. One neuro-fuzzy controller is prepared for each posture region. The structure of the neuro-fuzzy controller is basically the same as the conventional simplified fuzzy controller since it can be easily designed based on out anatomical knowledge and the results of previously performed experiment. However, the weight of the consequent part of control rules for the elbow motion assist is described by equation in order to take into account the sub-effect caused by shoulder motion. Therefore, the main-effect of each muscle is taken into account in the antecedent part and the sub-effect of some muscles is taken into account in the consequent part in this neuro-fuzzy control method. Even though there exists difference in anatomy and the way of muscle use between persons, the neuro-fuzzy controllers are able to adapt themselves to any robot user by adjusting both the antecedent part and the consequent part of the controllers using the back-propagation learning algorithm. The architecture of the neuro-fuzzy controller is shown in Fig. 5. Here, Σ means the summation of the inputs and Π means the multiplication of the inputs. Two kinds of nonlinear functions

(f_G and f_S) are applied to express the membership function of the neuro-fuzzy controller.

$$f_s(u_s) = \frac{1}{1+e^{-u_s}} \tag{2}$$

$$u_s(x) = w_0 + w_i x \tag{3}$$

$$f_G(u_G) = e^{-u_G^2} \tag{4}$$

$$u_G(x) = \frac{w_0 + x}{w_i} \tag{5}$$

where w_0 is a threshold value and w_i is a weight.

The initial fuzzy IF-THEN control rules are designed based on the analyzed human elbow and shoulder motion patterns in the pre-experiment, and then transferred to the neural network form. The EMG characteristics of human elbow and shoulder muscles studied in another research [16]-[19] are also taken into account. The input variables for the neuro-fuzzy controller are 8 kinds of MAVs of EMG. Three kinds of fuzzy linguistic variables (ZO, PS, and PB) are prepared for the MAVs of EMG.

The outputs of the neuro-fuzzy controller are the torque command for shoulder motion, and the desired impedance parameters and the desired angle for elbow motion of the exoskeleton system. The torque command for the shoulder joint of the exoskeleton system is then transferred to the force command for each driving wire. Force control is carried out to realize the commanded desired force in driving wires by the driving motors for shoulder motion of the exoskeleton system. Impedance control is performed with the derived impedance parameters and the derived desired angle for the elbow joint control of the exoskeleton system.

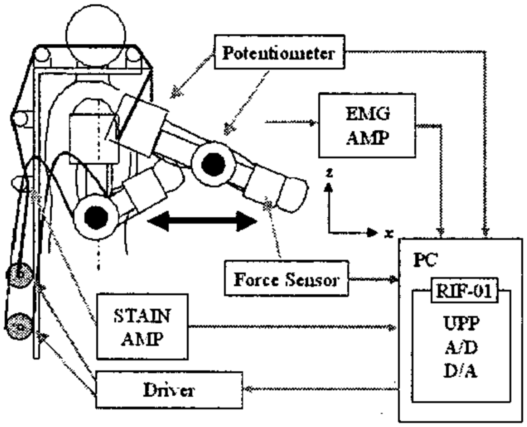
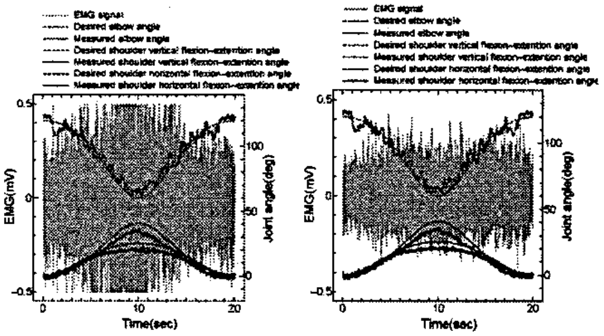


Figure 6. Experimental setup.

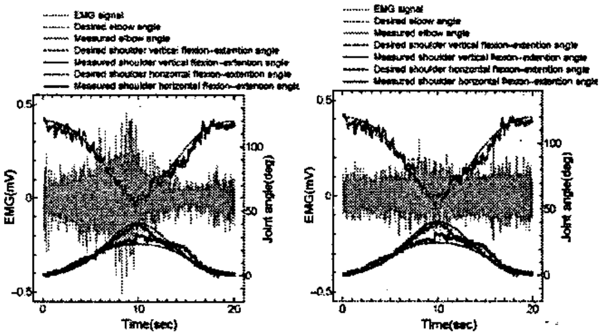
E. Controller Adaptation

The controller adaptation must be performed to realize the desired motion assist for anybody. Consequently, the controller should be able to adapt itself to physical and physiological condition of any user. Furthermore, the assist level by the exoskeleton should be adjusted according to the user's condition until the amount of the EMG signals of the user's muscles becomes the desired level. In this study, adjustment of the controller is performed using the back-propagation learning algorithm. All of antecedent part and some of consequence part of the fuzzy IF-THEN control rules are adjusted during the controller adaptation process.



Ch. 1 Ch. 5

(a) without assist



Ch. 1 Ch. 5

(b) with assist

Figure 7. Experimental results of the subject A.

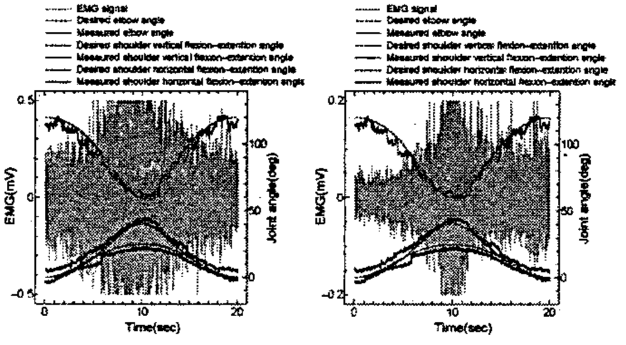
IV. EXPERIMENT

In order to evaluate the effectiveness of the proposed control method for the exoskeleton, upper-limb motion assist (power assist) experiment has been carried out with three healthy human subjects (Subject A and B are 22 years old males, Subject C is 23 years old male). The experimental setup is shown in Fig. 6. In order to examine the effectiveness of the proposed exoskeleton system in motion assist for both the elbow and shoulder joint of the human subject, cooperative motion of the elbow and shoulder joints is performed in the experiment. In this experiment, human subjects are supposed to move their wrist forward diagonally on the horizontal plane surface from the initial position and backward diagonally again to the initial position following the target trajectory with a 2kg weight in their hand. The initial position of the upper-limb is set to be 0 [deg] in both horizontal and vertical flexion angle of the shoulder joint, and 120 [deg] in flexion angle of the elbow joint. The desired trajectory of the wrist on the horizontal plane surface is described as:

$$(x, y) = (340[\mathrm{mm}]*\sin(30[\mathrm{deg}])*\sin(0.05t),\ 340[\mathrm{mm}]*\cos(30[\mathrm{deg}])*\sin(0.05t)). \qquad (6)$$

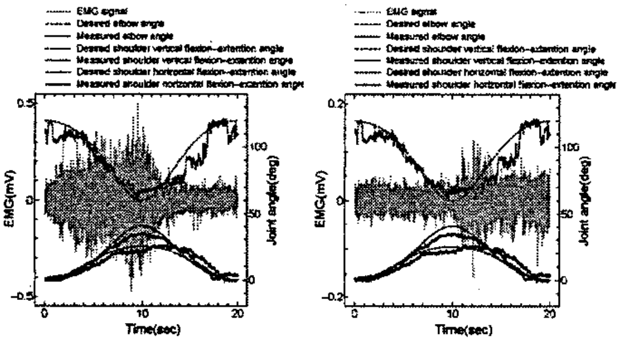
(1)

All experiment is performed with and without the assist of the exoskeleton system for comparison. If the exoskeleton system effectively assists the upper-limb motion, the activity levels of the EMG signals of the activated muscles are supposed to be reduced.



Ch. 1 Ch. 5

(a) without assist

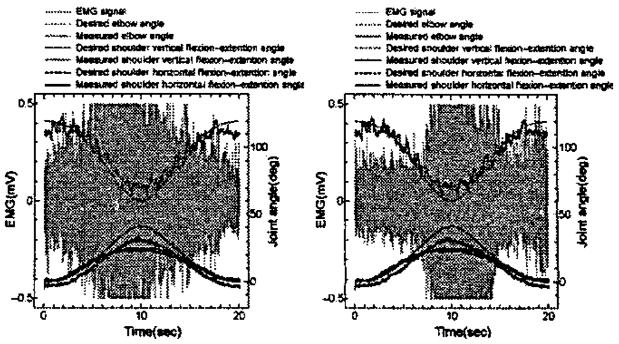


Ch. 1 Ch. 5

(b) with assist

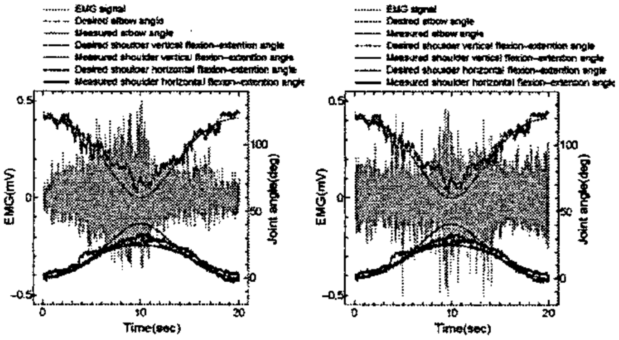
Figure 8. Experimental results of the subject B.

The experimental results of the Subject A without and with assist of the proposed exoskeleton system are shown in Fig. 7 (a) and (b), respectively. Only the results the EMG signals of ch. 1 (anterior part of deltoid) and ch. 5 (medial part of biceps), which represent the shoulder and elbow muscles, are depicted here. The experimental results of the Subject B and C are shown in Fig. 8 and 9, respectively. From these experimental results, one can see that the activation levels of the EMG signals of the elbow and shoulder muscles were reduced when the human subjects' motions were assisted by the exoskeleton. These results show the effectiveness of the proposed exoskeleton system and its control method in human upper-limb motion assist.



Ch. 1 Ch. 5

(a) without assist



Ch. 1 Ch. 5

(b) with assist

Figure 9. Experimental results of the subject C.

V. CONCLUSIONS

In this paper, we proposed a control method for a 3DOF exoskeleton system considering the effect of bi-articular muscles in order to assist the upper-limb motion of any physically weak persons such as elderly, disabled, and injured persons. The proposed control method consists of three stages (first stage: input signal selection stage, second stage: posture region selection stage, and third stage: neuro-fuzzy control stage. The skin surface electromyogram (EMG) signals, which directly reflect the human motion intention, are mainly used as controller input signals. In the neuro-fuzzy controller, the main-effect of each muscle is taken into account in the antecedent part and the sub-effect of some muscles is taken into account in the consequent part. The effectiveness of the proposed system was evaluated by experiment.

ACKNOWLEDGMENT

The authors would like to thank Mr. T. Tanaka, Mr. R. Esaki, Mr. Y. Sakamoto, and Mr. R. Ichiyama for their cooperation in the experiment.

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