A Study of an EMG-Based Exoskeletal Robot for Human Shoulder Motion Support*

Kazuo KIGUCHI**, Koya IWAMI**, Keigo WATANABE** and Toshio FUKUDA***

We have been developing exoskeletal robots in order to realize the human motion support (especially for physically weak people). In this paper, we propose a 2-DOF exoskeletal robot and its method of control to support the human shoulder motion. In this exoskeletal robot, the flexion-extension and abduction-adduction motions of the shoulder are supported by activating the arm holder of the robot, which is attached to the upper arm of the human subject, using wires driven by DC motors. A fuzzy-neuro controller is designed to control the robot according to the skin surface electromyogram (EMG) signals in which the intention of the human subject is reflected. The proposed controller controls the flexion-extension and abduction-adduction motion of the human subject. The effectiveness of the proposed exoskeletal robot has been evaluated experimentally.

Key Words: Human Motion Support, Exoskeletal Robots, Fuzzy-Neuro Control, EMG, Shoulder Motion

1. Introduction

A decrease in the birthrate and aging are progressing in Japan and several countries. In these societies, it is important that the physically weak people can take care of themselves somehow. Thus, we have been developing exoskeletal robots to support human motion especially for the physically weak people such as the elderly persons(11)-(16) described above. In everyday life, shoulder motion is very important since it is involved in a lot of daily work. Furthermore, some disabled persons have functional disorder in their proximal muscles such as the shoulder joint muscles, rather than their distal muscles. Consequently, supporting the shoulder motion of a physically weak person or a disabled person is very important. Recent progress of robotic technology brings a lot of benefits not only in the industry, but also in many other fields such as welfare and medicine. It is important to apply robotic technology to help disabled people who lost some of their original function by supporting their motion(17)-(18), or by making up their lost function(19)-(21). However, very little research on shoulder motion support has been done up to now because of the complexity of the shoulder anatomy.

The electromyogram (EMG), which contains biological information to understand patient's muscle activities, can be used as input information for the robotic prosthetic devices(22)-(23). The EMG signal is important for those devices to understand how the human subject intends to move. However, it is not easy to predict the shoulder motion only from EMG signals in a short time, since many muscles are involved in the shoulder motion(24)-(25). Furthermore, it is difficult to obtain the same EMG signal for the same motion even from the same person since the EMG signal is a biologically generated signal. Many factors such as fatigue of patients affect the biological signal(26). Moreover, different patients generate different levels of the EMG signal. Consequently, it is important that the system is capable to adapt itself to

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** Department of Advanced Systems Control Engineering, Saga University, 1 Honjomachi, Saga-shi, Saga 840-8502, Japan. E-mail: kiguchi@me.saga-u.ac.jp  
*** Center of Cooperative Research in Advanced Science and Technology, Nagoya University, 1 Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
the physiological condition of each human subject in an on-line manner.

In this paper, we propose a 2-DOF exoskeletal robot to support human shoulder motion as a step toward an exoskeletal robot that support whole body motion in everyday life. The exoskeletal robots, which are sometimes called as power suits, man amplifiers, man magnifiers, or power assist systems, have been studied for a long time for the purpose of military and industry use. However, those systems were not suitable for human motion support in everyday life since human subjects have to manipulate the robot system using extender systems. Furthermore, unexpected and/or undesired motion for human subjects might be generated when an unexpected external force is applied accidentally on the force sensors in those systems, since only the signals from the force sensors are used to control the robot systems.

In this study, the proposed robot system is supposed to help the shoulder motion of physically weak people in everyday life. In the proposed exoskeletal robot, the flexion-extension and abduction-adduction motions of the human subject are helped by activating the arm holder of the robot, which is attached to the upper arm of the human subject, using wires driven by DC motors. Since the robot is supposed to be used for everyday life situations of human subjects, its motion has to be very flexible. In order to produce flexible shoulder motion, a fuzzy-neuro controller is proposed to control the motion of the robot according to the skin surface EMG signals that reflect the human subject’s intentions. The physiological control can be created by this control method. Since the fuzzy-neuro controller is able to adapt itself to the physiological condition of any human subject in an online manner, the proposed exoskeletal robot is applicable to any human subject. In order to make the fuzzy-neuro controller adapt to the physiological condition of each human subject efficiently, the teaching equipment and the fuzzy selection of the evaluation function are used and introduced in this paper. The effectiveness of the proposed exoskeletal robot has been evaluated experimentally.

2. Exoskeletal Robot System

Figure 1 shows the proposed exoskeletal robot for human shoulder motion support. The exoskeletal robot consists of a frame, two links, an arm holder, two DC motors [Harmonic Drive System Co.], drive wires, and wire tension sensors (strain gauges). The robot worn by a human subject is supposed to help the subject’s shoulder joint motion by manipulating the subject’s upper arm using DC motors. Considering the fact that many physically weak people use wheelchairs, the heavy weight parts of the proposed exoskeletal robot (i.e., the DC motors) are supposed to be installed in the chair. The other parts of the exoskeletal robot are directly attached to the human subject. The joint between link-1 and link-2 is supposed to be located just below the armpit of the human subject. The flexion-extension and abduction-adduction motions of the shoulder (see Fig.2) are supported by activating the arm holder of the robot, which is connected to link-2 and attached to the upper arm of the human subject, using wires driven by DC motors. The shoulder angle is measured by potentiometers attached to the links of the robot. The wire tension (driving force) is measured by the wire tension sensors. The signals from the wire tension sensors are sampled at a rate of 2 kHz (the EMG signals are also sampled at the same time) and low-pass filtered at 8 Hz.

The skin surface EMG signals of the shoulder muscles, which imply the human subject’s intention, are used as input to control the robot. The location of the electrodes on the shoulder muscles is depicted in Fig.3. The electrodes are located on the anterior, posterior and the middle part of the deltoid, biceps, triceps, pectoralis major, infraspinatus, and teres major and those are connected to ch.1 - ch. 8, respec-
degrees in extension, 180 degrees in abduction, and 75 degrees in adduction. Considering the practical application in everyday life, the shoulder motion limitations of the proposed robot are 0 degrees in extension and adduction, 90 degrees in flexion, and 90 degrees in abduction. The maximum angular velocity of the motor is limited by the hardware, as a safety measure. The maximum torque of the robot (i.e., the maximum current of the motor) is also limited by both the hardware and the software for safety. Furthermore, there is an emergency stop switch beside the robot.

3. Human Shoulder Motion

The human shoulder joint is moved in 3-DOF (flexion-extension, abduction-adduction, and internal-external rotation) by many muscles. By adjusting the amount of force generated by the shoulder muscles, the shoulder motion can be moderately controlled. The muscle activity level can be described by the EMG signal. In order to design the control system of the exoskeletal robot, eight kinds of skin surface EMG signals (Fig. 3) have been analyzed during the human shoulder motion (flexion-extension, abduction-adduction, and horizontal flexion-extension motion as shown in Fig. 2) at the pre-experiment. The amplified EMG signals are sampled at a rate of 2 kHz in this study, since the power density spectra of the EMG contains most of its power in the frequency range of 5 - 500 Hz at the extremes. Although it is difficult to use raw data of EMG as input signals of the controller, features have to be extracted from the raw EMG data. In this study, Waveform Length (WL) is used as the feature expressing 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:

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

where $x_k$ is the $k$th sample voltage value, $x_{k-1}$ is $(k-1)$th sample voltage value, and $N$ is the number of samples in the segment. The number of samples is set to be 100 in this study. An example of the WL
obtained in the pre-experiment is shown in Fig. 4.

4. Control of the Exoskeletal Robot

The fuzzy neuro control method is proposed to control the shoulder motion of the exoskeletal robot based on the skin surface EMG signals of the shoulder muscles, which directly imply the human subject's intention. The initial fuzzy IF-THEN control rules of the fuzzy-neuro control are designed based on the analyzed human subject's shoulder motion patterns in the pre-experiment. The EMG characteristics of human shoulder muscles studied in another research\(^{[12][14]}\) are also taken into account.

The input variables of the fuzzy-neuro control are the WL of eight kinds of muscles. Three kinds of fuzzy linguistic variables (ZO: zero, PS: positive small, and PB: positive big) are prepared for each WL of EMG. The output of the fuzzy-neuro controller is the torque command used to generate the desired shoulder motion of the exoskeletal robot. The torque command for the exoskeletal robot joints is then transferred to the force command for each driving wire. The relationship between the torque command for the exoskeletal robot joints and the force command for driving wires is written as the following equation:

\[
\tau = J^T f_a \tag{2}
\]

where \(\tau\) is the torque command vector for the exoskeletal robot joints, \(f_a\) is the force command vector for the driving wires, and \(J\) is the Jacobian which relates the exoskeletal robot joint velocity to the driving wire velocity. Force control is carried out to realize the desired force (commanded force) in the driving wires by the driving motors. PD control has been applied for the force control law.

In the fuzzy-neuro controller, 18 kinds of fuzzy IF-THEN rules are prepared to generate the desired torque of the exoskeletal robot. The architecture of the fuzzy neuro controller is depicted in Fig. 5. Here, \(\Sigma\) means the sum of the inputs and \(\Pi\) means the multiplication of the inputs. The fuzzifier layer, in which each neuron represents a membership function for the input, consists of 24 neurons, the rule layer consists of 18 neurons and the defuzzifier layer consists of 4 neurons. Two kinds of nonlinear functions \((f_c\text{ and } f_a)\) are applied to express the membership function of the fuzzy-neuro controller.

\[
f_a(u_t) = \frac{1}{1 + e^{-w_t u_t}} \tag{3}
\]

\[
u_s(x) = w_0 + w_i x \tag{4}
\]

\[
f_c(u_c) = e^{-w_c} \tag{5}
\]

\[
u_c(x) = \frac{w_0 + w_i x}{w_i} \tag{6}
\]

where \(w_0\) is a threshold value and \(w_i\) is a weight.

The Gaussian function \(f_c\), \(w_0\) is a mean value and \(w_i\) is a deviation of the membership function. The process of the fuzzy neuro controller is the same as that of the ordinal simplified fuzzy controllers. Consequently, the output of the fuzzy-neuro controller is calculated with the following equation:

\[
O = \frac{\sum w_{re} y_{re}}{\sum y_{re}} \tag{7}
\]

where \(O\) represents the output vector, \(y_{re}\) denotes the degree of fitness of the \(i\)th rule, and \(w_{re}\) is the weight for the \(i\)th rule.

It is important that the controller adapts itself to the physiological condition of each human subject in an on-line manner, since the EMG signal is a biologically generated signal. The adaptation ability of the fuzzy-neuro controller enables the controller to fit the physiological condition of each human subject. The adaptation of the fuzzy-neuro controller is carried out by adjusting each weight of the fuzzy-neuro controller to minimize the amount of motion error, which is directly given by the human subject using the teaching equipment (Fig. 6), attached to the hand of the other arm. The angle of link-1 of the teaching equipment is supposed to correspond to that of link-1.

Fig. 5 Architecture of fuzzy-neuro controller
of the exoskeletal robot, and the angle of link 2 of the teaching equipment is supposed to correspond to that of link 2 of the exoskeletal robot. In the teaching process, the human subject instructs the fuzzy neuro controller about his/her desired shoulder motion by demonstrating the same motion using his/her wrist manipulating the teaching equipment. In this study, both the antecedent part and the consequent part of the fuzzy IF-THEN control rules are supposed to be adjusted by the back-propagation learning method in an online manner. The back-propagation learning algorithm is applied to minimize the squared error function written below.

\[
E = \begin{cases} 
\frac{1}{2} (q_d - q)^2 & \text{IF } (q_d - q) \text{ is not ZERO} \\
0 & \text{IF } (q_d - q) \text{ is ZERO}
\end{cases} \tag{8}
\]

where \(q_d\) is the angle of the desired motion indicated by the human subject using the teaching equipment and \(q\) is the measured joint angle of the exoskeletal robot. In order to avoid the useless adaptation caused from small errors, the fuzzy variable ZERO is applied to express that the error of the exoskeletal robot is almost zero.

5. Experiment

In order to evaluate the effectiveness of the proposed exoskeletal robot system, experiments have been performed with three healthy human male subjects (Subject A and B are 24 years old, and Subject C is 23 years old). Figure 7 shows the experimental setup. The amplified EMG signals are sampled at a rate of 2 kHz and the signals from the wire tension sensors are sampled at a rate of 2 kHz and low-pass filtered at 8 Hz.

The target following experiments have been carried out with and without support of the exoskeletal robot in order to verify the controllability of the robot. In the experiment, the target trajectory (flexion-extension and horizontal flexion-extension angle) of the shoulder is displayed on the monitor, and a human subject is supposed to make his shoulder angles follow this with a 500 g weight in his hand. The generated shoulder trajectory is supposed to be very close to the target trajectory if the exoskeletal robot is well controlled, and the EMG levels of shoulder muscles are supposed to be lower if the exoskeletal robot effectively supports the shoulder motion of the human subject. Two kinds of target trajectories (trajectory 1 and 2) are prepared in this experiment.

Figures 8 and 9 show the experimental results (EMG signals and shoulder motion) of subject A for target trajectory 1 with and without support of the exoskeletal robot, respectively. Since the anterior, posterior and the middle parts of the deltoid are mainly used for these shoulder motions, the EMG signals of these muscles are presented. The experimental results (EMG signals and shoulder motion) of subject A for target trajectory 2 with and without support of the exoskeletal robot are depicted in Figs. 10 and 11, respectively. Comparing the results in Figs. 8 and 9 and in Figs. 10 and 11, one can see that the motion support by the exoskeletal robot results in a little better target following. These results show the exoskeletal robot is controlled in accordance with the subject's intention. One can also see that the EMG levels of the deltoid during the shoulder motion are much lower when the human motion is supported by the exoskeletal robot. That means the human motion is effectively supported by the proposed exoskeletal robot.

Figures 12 and 13 show experimental results of the subject B for target trajectory 1 with and without support of the exoskeletal robot, respectively. Again, the EMG levels of the deltoid during the shoulder motion become much lower when the human motion is supported by the exoskeletal robot. Furthermore, the target following result is a little better when the
Fig. 8  Experimental results for the target trajectory 1 with support of the exoskeletal robot (Subject A)

Fig. 9  Experimental results for the target trajectory 1 without support of the exoskeletal robot (Subject A)

Fig. 10  Experimental results for the target trajectory 2 with support of the exoskeletal robot (Subject A)

Fig. 11  Experimental results for the target trajectory 2 without support of the exoskeletal robot (Subject A)
Fig. 12 Experimental results for the target trajectory 1 with support of the exoskeletal robot (Subject B)

Fig. 14 Experimental results for the target trajectory 1 with support of the exoskeletal robot (Subject C)

Fig. 13 Experimental results for the target trajectory 1 without support of the exoskeletal robot (Subject B)

Fig. 15 Experimental results for the target trajectory 1 without support of the exoskeletal robot (Subject C)
human motion is supported by the exoskeletal robot. Similar experimental results are obtained with the subject C as shown in Figs. 14 and 15. From these experimental results, one can verify that the exoskeletal robot can effectively support the shoulder motion of any human subject because of the adaptation ability of the fuzzy-neuro controller.

6. Conclusions

A 2-DOF exoskeletal robot for human shoulder motion support and its control system have been proposed for physically weak people. Flexible and physiological shoulder motion support can be created by controlling the exoskeletal robot based on EMG signals of the shoulder muscles with the proposed control system. The adaptation ability and the effectiveness of the proposed exoskeletal robot have been evaluated by experiment. The proposed exoskeletal robot system could be used for the rehabilitation of the shoulder motion since the system is activated based on the shoulder muscles' activity level. We would like to continue this study toward the production of a full motion support exoskeletal robot.

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