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An Exoskeleton for Human Elbow and Forearm Motion Assist

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Abstract - We present an exoskeleton to assist elbow and forearm motion of physically weak persons such as elderly, injured, or disabled persons. The forearm pronation/supination motion and the elbow flexion/extension motion, which are essential motions for the activities of daily living, are assisted by the proposed exoskeleton. The electromyogram (EMG) signals of muscles in forearm and upper-arm of the exoskeleton's user and the wrist force are also used as input information for the controller. By applying the EMG signals as main input signals to the controller, automatic control can be realized for the physically weak persons without manipulating any equipment. Fuzzy control has been applied to realize the natural and flexible motion assist. Experiment has been performed to evaluate the effectiveness of the proposed exoskeleton.

I. INTRODUCTION

A decrease in the birthrate and aging are progressing in several countries. In that society, it is important that physically weak persons take care of themselves without the help of other persons. We have been developing exoskeletons [1]-[3] for motion assist of physically weak persons such as elderly, injured, or disabled persons. The physically weak persons would be able to take care of themselves with the help of the exoskeletons. The upper-limb motion (shoulder, elbow, and wrist motion) is especially important for people to perform activities of daily living. The exoskeletons for elbow motion assist [1], shoulder motion assist [2], upper-limb motion assist [3][4], and knee motion assist [5] have been proposed for daily use or rehabilitation up to the present. This paper presents an exoskeleton for elbow and forearm motion assist for physically weak persons. The forearm pronation/supination motion and the elbow flexion/extension motion, which are essential motions for the activities of daily living, are assisted by the proposed exoskeleton. Since the mechanism and the control method for elbow motion assist are explained in our previous paper [1], this paper concentrates on the forearm motion assist.

The electromyogram (EMG) signals of human muscles are important signals to understand the motion intension of the user. Therefore, the EMG signals have been used as input information for the control of many robotic systems [6]-[8]. The EMG signals of muscles in forearm and upper-arm of the exoskeleton's user are used as main input information for the control of the proposed exoskeleton in this study as well. The wrist force is also used as subordinate input information for the controller. By applying the EMG signals as main input signals to the controller, automatic control can be realized for the physically weak persons without manipulating any equipment. This kind of control is especially important for the system used by elderly, injured, or disabled persons. The automatic control of the exoskeleton must be performed in real-time. The time delay more than 200ms is not allowed for the exoskeleton which is directly attached to the human user. The requirement for the exoskeleton is stricter than that for the artificial arm on this point. The forearm and upper-arm, however, consist of many kinds of muscles which are involved in many motions [9][10]. Therefore, it is not easy to apply EMG signals of muscles of the forearm and upper-arm as input signals to the controller. We have performed the experiment to find out certain patterns of EMG signals for the motion of forearm and elbow. Then, fuzzy IF-THEN control rules have been proposed based on the experimental results. By applying the fuzzy controller for the control of the proposed exoskeleton, natural and flexible motion control has been realized.

II. EXOSKELETON

The architecture of the proposed exoskeleton is shown in Fig. 1. The exoskeleton consists of two links, two DC motors, a ballscrew drive shaft, a ballscrew support frame, a driving wire, a wrist frame, an inner and an outer wrist holder, a wrist cover, potentiometers, and a wrist force sensor. The user is supposed to attach his/her wrist in the wrist holder. Then the wrist holder is attached to the wrist cover as shown in Fig. 2. The link-1 is directly attached to the lateral side of the user's upper-arm. When the exoskeleton is attached to the user, the axis of the exoskeleton's elbow joint is set to be the same as the user's elbow joint axis passing through the centers of the arcs formed by the capitellum and the trochlear sulcus. The strain-gauge based wrist force sensor is installed in the wrist holder (between the inner and outer wrist holder) in order to measure the force

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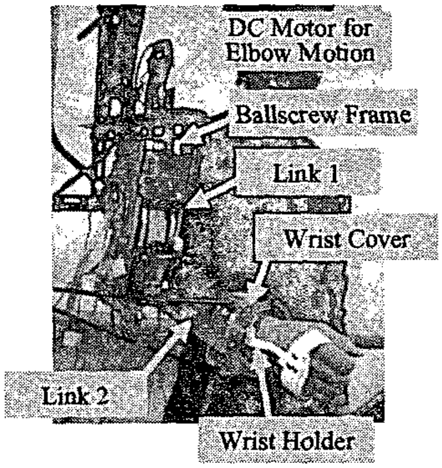
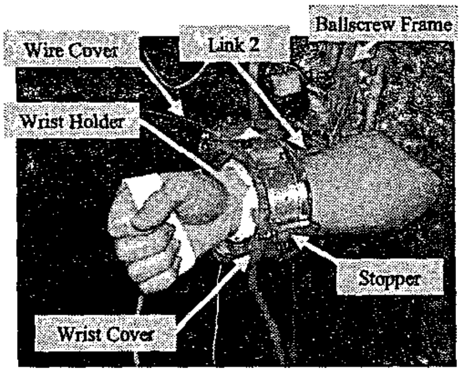


(a) view from the lateral side



(b) view from the medial side

Fig. 1 Architecture of the exoskeleton

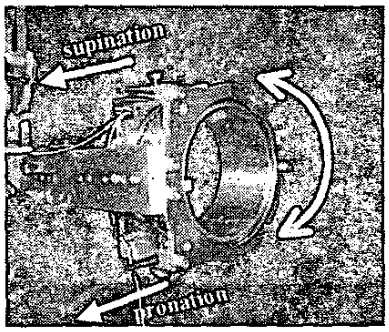


Fig. 2 Wire driven system

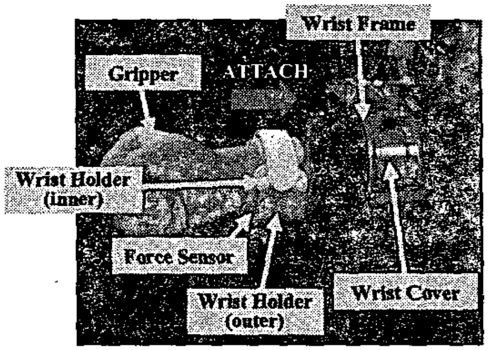
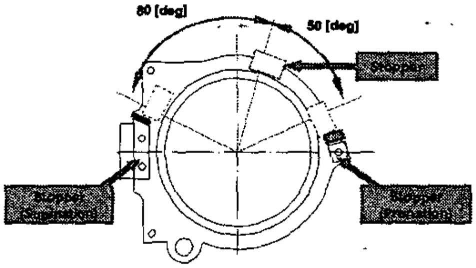


Fig. 3 Attachment of the wist holder



View from the front

Fig. 4 Movable range of the exoskeleton

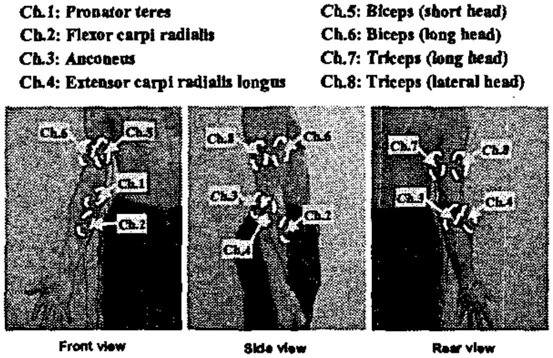
caused by the motion difference between the user's wrist and the exoskeleton's one. The rotation angle of the wrist cover with respect to the wrist frame (i.e., forearm pronation/supination angle) and that of the link-2 with respect to the link-1 (i.e., elbow flexion/extension angle) are measured by the potentiometers.

In order to generate the elbow flexion (or extension) motion, 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, using the DC motor [1]. The forearm pronation/supination motion (the rotational motion of the wrist cover with respect to the wrist frame) is generated by a wire which is drove by the other DC motor as shown in Fig. 3.

Usually, the limitation of the movable range of forearm pronation/supination motion is 50-80 degrees in pronation and 80-90 degrees in supination, and that of elbow flexion/extension motion is 145 degrees in flexion and -5 degrees in extension. Considering the safety of the user, the limitation of the exoskeleton's forearm motion is decided to be 50 degrees in pronation and 80 degrees in supination, and that of the exoskeleton's elbow motion is decided to be 120 degrees in flexion and 0 degrees in extension. The stoppers are attached on the exoskeleton to physically prevent the forearm pronation/supination motion from exceeding the movable range as shown in Fig. 4.

III. CONTROLLER

The proposed exoskeleton is controlled based on the EMG signals and the wrist force. In the proposed control method, the



Front view Side view Rear view

Fig. 5 Location of electrodes

motion assist is carried out based on the wrist force when the amount of the EMG activity levels is little. By applying sensor fusion with the EMG signals and the wrist force, the error motion caused by little EMG levels and the unexpected motion caused by the external force affecting to the user's arm can be avoided. Since the elbow joint motion control method is already explained in our previous paper [1], the forearm motion control method is explained in this section.

Since the forearm consists of many kinds of muscles, which are involved in finger, wrist, and elbow motion as well as forearm pronation/supination motion, it is not very easy to predict the forearm pronation/supination motion intension of the user based on the EMG signals of the forearm and upper-arm muscles. Furthermore, the upper-limb posture affects the amount of the EMG signals for the same forearm pronation/supination motion. Fuzzy control has been applied to realize flexible and real time control based on the EMG signals. In order to design fuzzy IF-THEN control rules, preliminary experiment was performed.

The forearm pronation motion is generated by the muscles of pronator teres, pronator quadratus, brachioradialis, anconeus, and flexer carpi radialis, and the forearm supination motion is generated by the muscles of biceps, supinator, brachioradialis, extensor carpi radialis longus, and extensor carpi radialis brevis. In the proposed controller, eight kinds of EMG signals (ch.1: pronator teres, ch.2: flexer carpi radialis, ch.3: anconeus, ch.4: extensor carpi radialis longus, ch.5: proximal part of biceps, ch.6: lateral part of biceps, ch.7: proximal part of triceps, and ch.8: lateral part of triceps) are measured to control the forearm pronation/supination motion and the elbow flexion/extension motion as shown in Fig. 5. Three of them (ch.1: pronator teres, ch.2: flexer carpi radialis, and ch.3: anconeus) are used to figure out the pronation motion, and another three of them (ch.4: extensor carpi radialis longus, ch.5: proximal part of biceps, and ch.6: lateral part of biceps) are used to figure out the supination motion. Four of them (ch.5: proximal part of biceps, ch.6: lateral part of biceps, ch.7: proximal part of triceps, and ch.8: lateral part of triceps) are used to for the elbow flexion/extension motion [1].

Since there is difficulty in using raw data of EMG for input information of the controller, features have to be extracted from the raw EMG data. In this study, Mean Absolute Value (MAV) [11] has been applied as the feature extraction method of the EMG levels for the fuzzy-neuro controllers. The equation of MAV is written as:

$$MAV = \frac{1}{N}\sum_{k=1}^{N}|x_k| \qquad (1)$$

where x_k is the voltage value at kth 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 0.5ms in this study.

The input variables for the controller are MAVs of eight kinds of the EMG signals and the generated wrist force measured by the wrist force sensor. In the control rules, we consider the generated wrist force is more reliable when the exoskeleton's user activates the muscles little (when the EMG levels of the user are low), and the EMG signals are more reliable when the user activates the muscles a lot (when the EMG levels of the user are high). In other words, the exoskeleton is controlled based on the generated wrist force when the EMG levels of the subject are low, and the exoskeleton is controlled based on the EMG signals when the EMG levels of the user are high. Consequently, the exoskeleton can be controlled in accordance with the human user's intention. By applying sensor fusion with the 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.

When the exoskeleton's user activates the muscles, fuzzy control is performed based on MAVs of eight kinds of the EMG signals. Three kinds of linguistic variables (PS: Positive Small, PM: Positive Medium, and PB: Positive Big) are prepared for each MAV. Twelve kinds of fuzzy control rules are designed to generate the forearm pronation/supination motion based on MAVs of six kinds of the EMG signals. Sixteen kinds of fuzzy control rules are used to generate the elbow flexion/extension motion based on MAVs of four kinds of EMG signals [1].

When the exoskeleton's user does not activate the muscles for forearm pronation/supination motion, force control of the wrist force is performed based on the generated wrist force measured by the force sensor to make the exoskeleton pronate/supinate. The effect of the force-sensor-based control on the exoskeleton's pronation/supination motion is gradually reduced according to the amount of muscle activation levels on ch.1 (pronator teres) or ch.5 (proximal part of biceps).

IV.EXPERIMENT

In order to evaluate the effectiveness of the proposed exoskeleton, the experiment has been performed with healthy male subjects (both of them are 22 years old). The experimental setup is depicted in Fig. 6. Since the effectiveness of the exoskeleton for elbow flexion/extension motion assist was already verified in [1], the effectiveness for forearm pronation/supination motion

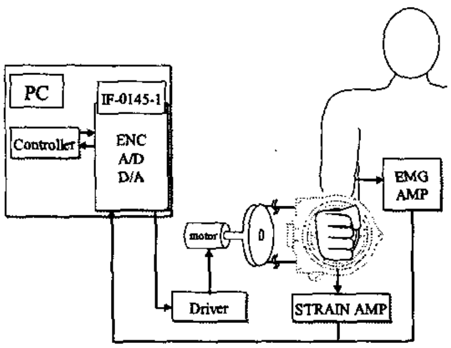


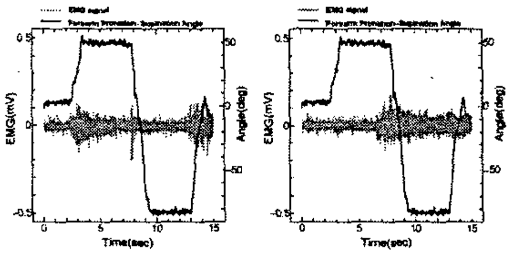
Fig. 6 Experimental setup

is evaluated in this paper. The 10,000 times amplified EMG signals are sampled at a rate of 2kHz and the signal from the force sensor is also sampled at a rate of 2kHz and low-pass filtered at 8Hz in the experiment. Every experiment has been performed with and without assist of the exoskeleton for comparison. The human subject is supposed to make his hand gently squeeze during the experiment as shown in Fig. 1. The activity levels of the EMG signals for the same motion are supposed to be reduced if the motion is effectively assisted by the exoskeleton.

For the first experiment, the forearm pronation/supination motion assist has been carried out when the elbow flexion angle is fixed at 0, 45, and 90 [deg]. In this experiment, the human subject is supposed to pronate 50 [deg] from the standard position, then supinate 130 [deg] within 15s. The experimental results of the subject A with and without assist of the exoskeleton when the elbow flexion angle is fixed at 90 [deg] are shown in Fig. 7. Here, only the experimental results of ch.1 (pronator teres) and ch.5 (proximal part of biceps) are depicted since they are the most active muscle for pronation and supination when the elbow is flexed, respectively. One can see that the EMG activity level of ch.1 was significantly reduced with assist of the exoskeleton when the forearm was pronating. Since the EMG activity level of ch.5 was small even without assist of the exoskeleton, the EMG activity level was not changed. The similar experimental results were obtained with the subject B.

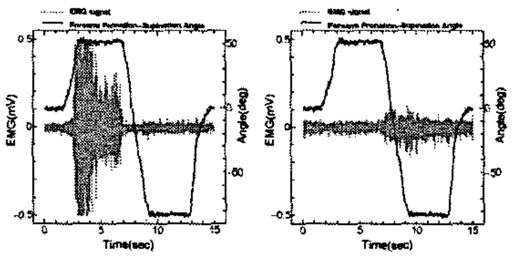
The experimental results of the subject A with and without assist of the exoskeleton when the elbow flexion angle is fixed at 0 [deg] are shown in Fig. 8. Here, only the experimental results of ch.3 (anconeus) and ch.5 (proximal part of biceps) are depicted since they are the most active muscle for pronation and supination when the elbow is extended, respectively. One can see that the EMG activity level of ch.3 was significantly reduced with assist of the exoskeleton when the forearm was pronating. Since the EMG activity level of ch.5 was also small even without assist of the exoskeleton, the EMG activity level was not changed. Again, the similar experimental results were obtained with the subject B.

When the elbow flexion angle is fixed at 45 [deg], the similar results were also obtained with the subject A and B.



ch. 1 **ch. 5**

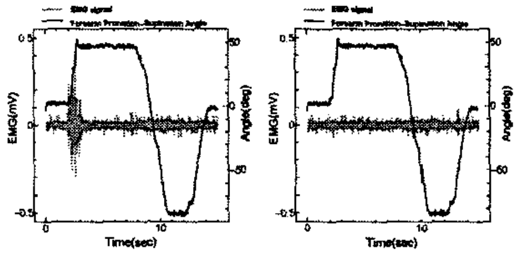
(a) with assist of the exoskeleton



ch. 1 **ch. 5**

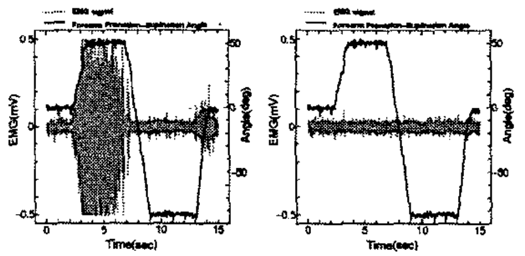
(b) without assist of the exoskeleton

Fig. 7 Experimental results with the subject A (elbow flexion angle: 90 [deg])



ch. 3 **ch. 5**

(a) with assist of the exoskeleton

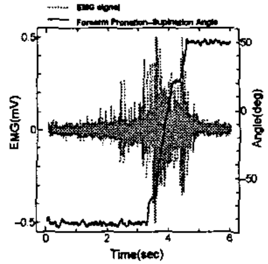


ch. 3 **ch. 5**

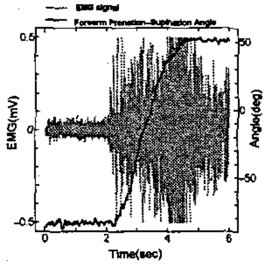
(b) without assist of the exoskeleton

Fig. 8 Experimental results with the subject A (elbow flexion angle: 0 [deg])

For the second experiment, the forearm pronation motion assist has been carried out under the external load generated by a rubber tube against the motion. In this experiment, the human subject is supposed to pronate 130 [deg] from the most supinated position within 6s. The experimental results of the subject A when the elbow flexion angle is fixed at 0 [deg] and 90 [deg]

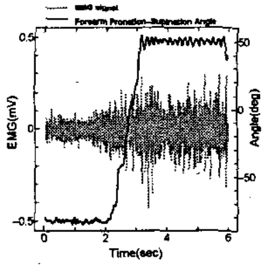


(a) with assist of the exoskeleton

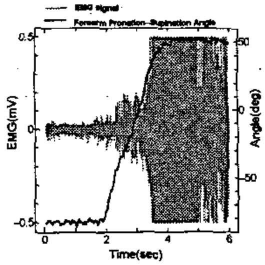


(b) without assist of the exoskeleton

Fig. 9 Experimental results of ch. 3 with the subject A
(elbow flexion angle: 0 [deg])

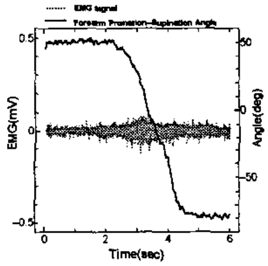


(a) with assist of the exoskeleton

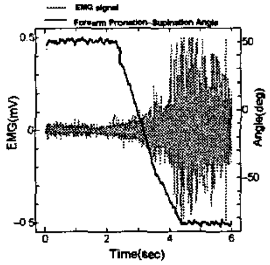


(b) without assist of the exoskeleton

Fig. 10 Experimental results of ch. 1 with the subject A
(elbow flexion angle: 90 [deg])

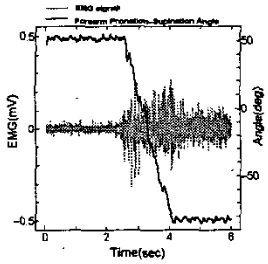


(a) with assist of the exoskeleton

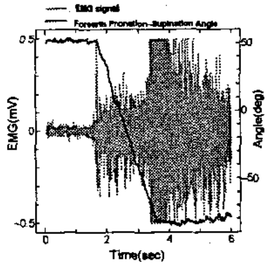


(b) without assist of the exoskeleton

Fig. 11 Experimental results of ch. 5 with the subject A
(elbow flexion angle: 0 [deg])



(a) with assist of the exoskeleton



(b) without assist of the exoskeleton

Fig. 12 Experimental results of ch. 5 with the subject A
(elbow flexion angle: 90 [deg])

are shown in Fig. 9 and Fig. 10, respectively. Here, only the experimental result of ch.3 (anconeus) or ch.1 (pronator teres) is depicted in Fig. 9 and Fig. 10, since it is the most active muscle in each experiment. One can see that the EMG activity level was significantly reduced when the pronation motion was assist of the exoskeleton. The similar experimental results were obtained with the subject B.

For the third experiment, the forearm supination motion assist has been carried out under the external load generated by a rubber tube against the motion. In this experiment, the human subject is supposed to supinate 130 [deg] from the most pronated position within 6s. The experimental results of the subject A when the elbow flexion angle is fixed at 0 [deg] and 90 [deg] are shown in Fig. 11 and Fig. 12, respectively. Here, only the experimental result of ch.5 (proximal part of biceps) is depicted since it is the most active muscle in each experiment. One can see that the EMG activity level was significantly reduced when the supination motion was assist of the exoskeleton. The similar experimental results were obtained with the subject B.

V.CONCLUSIONS

The exoskeleton for elbow and forearm motion assist has been proposed to help the activities of daily living for physically weak persons. The proposed exoskeleton is directly attached to the user's body and automatically assists the user's elbow and forearm motion in real-time mainly based on the EMG signals. Fuzzy control has been applied to realize the natural and flexible motion assist and sensor fusion. Experiment results showed the effectiveness of the proposed exoskeleton.

VI.ACKKNOWLEDGMENT

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