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# EMG-Based Control of an Exoskeleton Robot for Human Forearm and Wrist Motion Assist

Ranathunga Arachchilage Ruwan Chandra Gopura, *Student Member*, *IEEE,* Kazuo Kiguchi, *Member, IEEE*

*Abstract*—**We have been developing exoskeleton robots for assisting the motion of physically weak individuals such as elderly or slightly disabled in daily life. In this paper we propose an EMG-Based control of a three degree of freedom (3-DOF) exoskeleton robot for the forearm pronation/ supination motion, wrist flexion/extension motion and ulnar/ radial deviation. The paper describes the hardware design of the exoskeleton robot and the control method. The skin surface electromyographic (EMG) signals of muscles in forearm of the exoskeleton's user and the hand force/forearm torque are used as input information for the proposed controller. By applying the skin surface EMG signals as main input signals to the controller, automatic control of the robot can be realized without manipulating any other equipment. Fuzzy control method has been applied to realize the natural and flexible motion assist. An experiment has been performed to evaluate the proposed exoskeleton robot.**

## I. INTRODUCTION

It is important that the physically weak individuals take care of themselves in the present society, in which the birthrate is decreasing and aging are progressing. We have been developing exoskeleton robots [1]-[4] for assisting the motions of physically weak individuals such as elderly, injured, or disabled. The upper-limb motions (shoulder, elbow, and wrist motion) are especially important for people to perform daily activities. The exoskeletons for elbow motion assist [1], shoulder motion assist [2], upper-limb motion assist [3][5][6] and elbow and forearm motion assist[4], have been proposed for daily use or rehabilitation up to the present. This paper presents an exoskeleton robot for wrist flexion/extension motion, ulnar/radial deviation and forearm pronation/supination motion assist for physically weak people. The forearm pronation/supination motion, wrist flexion/extension motion and ulnar/radial deviation, which are essential motions for the daily activities, are assisted by the proposed exoskeleton. Some important daily activities, which involve wrist and forearm motion are brushing teeth, washing face and neck, shaving, eating with spoon, eating from hand, drinking from cup, pouring from bottle, opening a door, writing and painting, polishing surfaces and using a wheel chair and etc.

Although some exoskeletons have been proposed for wrist motion assist [6]-[9], there are undesired problems in their design. For example, the axes offset of flexion/extension axis and ulnar/radial deviation axis is not taken into account in the existing robots [8] [9], although it is important for the wrist exoskeleton to avoid the undesired pain for users. The robot user has to grip a link (palm holder) for wrist motions in almost all of the existing exoskeleton robots [6] [8] [9] (except ASSIST [7]), so that users' fingers won't be able to use for other purposes. The proposed exoskeleton robot is designed considering the above shortcomings and its' palm holder can be worn and the user does not have to grip it. TABLE.1 shows the differences between proposed robot and existing robots [6]-[9].

TABLE 1
DIFFERENCES BETWEEN EXISTING ROBOTS AND PROPOSED ROBOT

| Existing robot | Proposed robot |
|---|---|
| **ARMin** [6] | |
| No wrist ulnar/radial deviation | Wrist ulnar/radial deviation is available |
| Use cable drive and ball screw for power transmission | Use gear drives for power transmission |
| **ASSIST** [7] | |
| Use pneumatic soft actuators | Use gear drives and servo actuators |
| No wrist ulnar/radial deviation | Wrist ulnar/radial deviation is available |
| **University of Washington**[8] | |
| Use cable drives | Use gear drives |
| Bulky | Less bulk |
| **University of Salford** [9] | |
| Use soft actuators | Use gear drives and servo actuators |

The electromyographic (EMG) signals of human muscles are important signals to understand the motion intention of human. Therefore, the EMG signals can be used as input information for the control of many robotic systems [10]-[12]. The skin surface EMG signals of muscles in forearm of the exoskeletons' user are used as main input information for the control of the proposed exoskeleton robot. The hand force (The generated force between the robot and the hand of the robot user, when he tries to perform the motions of wrist flexion/extension and/or ulnar/radial deviation) and forearm torque (The generated torque between the wrist holder of the robot and the forearm of robot user, when he tries to perform forearm supination/pronation motion) are also used as subordinate input information for the controller. By applying the skin surface EMG signals as main input signals to the controller, automatic control can be realized for the physically weak persons without manipulating any equipment. Such kind of control is especially important for the system used by elderly, injured, or disabled persons. The automatic control of the exoskeleton robot must be performed in real-time. Since the forearm, consist of many kinds of muscles which are involved in many motions [13] [14], it is difficult to apply EMG signals of muscles of the forearm as input signals to the controller. Also

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R. A. R. C. Gopura is a doctoral student of the Saga University, Saga, Japan (e-mail: gopura@ieee.org).

K. Kiguchi is with the Saga University, Saga, Japan (phone: +81-952-28-8702; fax: +81-952-28-8587; e-mail: kiguchi@ieee.org).

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it is not easy to separate the motions. Fuzzy IF-THEN control rules have been newly designed after experimentally finding out the patterns of EMG signals for the motion of forearm and wrist. The fuzzy controller has been applied for the control of the proposed exoskeleton robot to obtain natural and flexible motion control.

This paper presents the hardware design of the exoskeleton robot and the control method. Experiment has been performed to evaluate the effectiveness of the proposed exoskeleton robot.

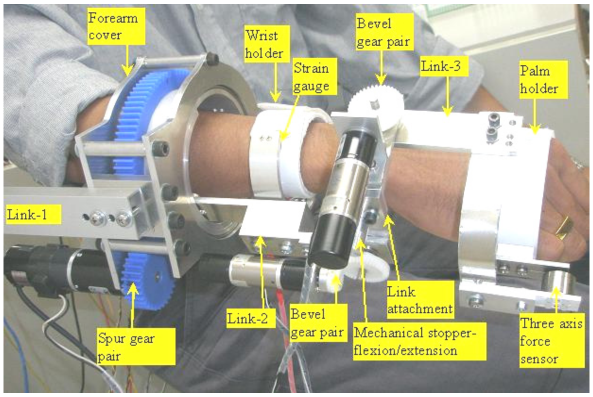
## II. HARDWARE DESIGN OF EXOSKELETON

### A. *Requirement of the Exoskeleton*

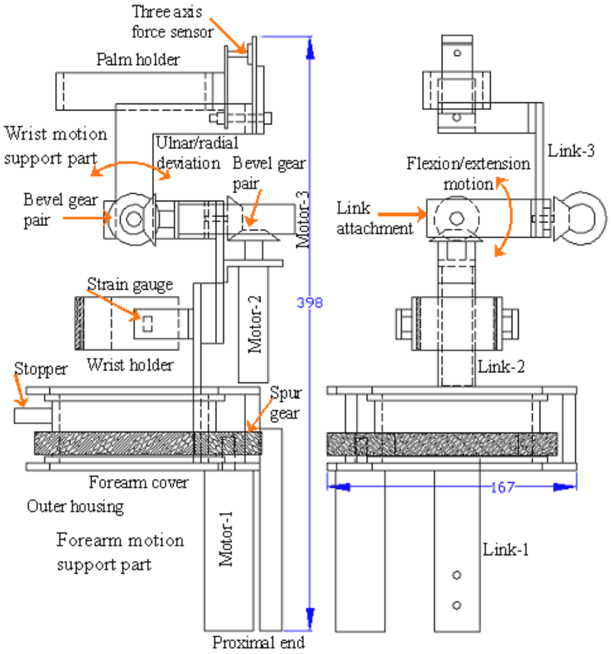
The exoskeleton robot should be adaptable to the human wrist in terms of segmental lengths, range of motion, location of center of rotation and the number of DOFs. The frames and motors of the exoskeleton robot should be located to eliminate disturbance to each motions of the robot and the robot should not affect the motion of all the fingers. The axis deviation of the ulnar/radial deviation axis and the flexion/extension axis is about 5 mm. The robot should provide the axis deviation and should be directly fixed to the human forearm. As the robot is in direct contact with the human user, the safety requirement is paramount. Since the robot is supposed to be used for everyday life of users, its motion has to be sufficiently flexible and smooth. In addition, it should be comfortable and easy to wear.

### B. *Mechanical Structure and Mechanism*

Figure1 shows the proposed exoskeleton robot for human wrist and forearm motion assist. The proposed exoskeleton robot [15] mainly consists of a forearm motion support part and a wrist motion support part, and it is directly attached to the user's forearm. The wrist motion support part consists of a L-shaped link attachment, two DC motors, two drive and driven bevel gear pairs (Gear ratio-1:2), a palm holder, a three axis force sensor and a link (LINK-3) which connect the palm holder and link attachment as shown in Fig. 1. The forearm motion support part consists of two links (LINK-1 and 2), a DC motor, a drive and driven spur gear pair (Gear ratio-1:3), a wrist holder, a forearm cover and torque sensors (Strain gauges). Proximal end of link-1 can be attached to the upper limb exoskeleton robot [3] which has been developed previously. Distal end of link-1 is attached to the outer housing of the forearm cover. The motor for pronation/ supination motion (Motor-1) is attached in outer housing of forearm cover. The outer housing of forearm cover and inner hollow cylinder are assembled through two bearings (Open REALI-SLIM®-radial contact type) such a way that the forearm can be inserted to the hole of the hollow cylinder. Therefore, the inner hollow cylinder of the forearm cover can be rotated with respect to the fixed outer housing. Link-2 is attached to the inner hollow cylinder of the forearm cover. The wrist holder is attached to link-2. The motor for wrist flexion/extension motion (Motor-2) is fixed on link-2. Link-2 is attached with L-shaped link attachment using a bearing and a shaft to form a revolute joint. The link attachment holds the motor for the wrist ulnar/radial deviation (Motor-3). Link-3 is attached to the link attachment using a shaft and bearing to form a revolute joint. The palm holder and a three axis force sensor are attached to link-3. The palm holder of the exoskeleton robot is attached to the palm of the user.



(a) Overall system



(b) Top view (Dorsal view) (c) Side view (Radial side)

Fig. 1. 3DOF wrist and forearm motion assist exoskeleton robot

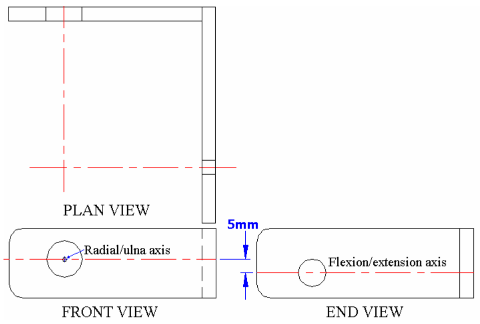


Fig. 2. Link attachment

The palm holder is positioned to transmit the torque properly via link-3 and not to obstruct the finger movement. The link attachment has been designed to provide the axes deviation of the ulna/radial deviation axis and the flexion/extension axis as shown in Fig. 2. The effective length of the exoskeleton robot is 398 mm and the width is 167 mm at the most wide location.

TABLE 2 MOVABLE RANGE

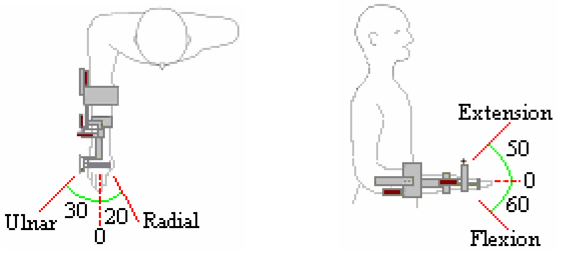
| Motion | Movable range of exoskeleton [Deg] | Average Movable range of Human [Deg] |
|---|---|---|
| Ulnar deviation | 30 | 35 |
| Radial deviation | 20 | 25 |
| Extension | 50 | 60 |
| Flexion | 60 | 70 |
| Pronation | 60 | 75 |
| Supination | 80 | 80 |

Sizes of all links, attachments and distances are designed using human anthropometry with 95th percentile. The palm holder and wrist holder are designed to wear easily and both have cushion material on the inner surface to have a comfortable wear.

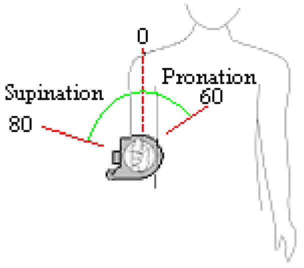
Considering the minimally required motion in daily activities and the safety of the user, the limitation of the movable ranges of the exoskeleton robot is decided as per TABLE 2. The movable range of the exoskeleton robot is shown in Fig. 3.

### C. Sensors and Actuators

All three motors are harmonic drive, super mini, RH series DC servo actuators with open collector type incremental encoders. The three axis force sensor (PD3-32-05-080 of NTTA) is attached between the distal end of the link-3 of the robot and palm holder of the robot user. Also torque sensors (Strain gauges) are attached on the connecting beams of link-2 and wrist holder as shown in Fig. 4. These force/torque sensors are used to perform force control of the robot.



(a) Wrist ulnar/radial deviation (b) Wrist flexion/extension



(c) Forearm pronation/supination motion

Fig. 3. Movable range of the exoskeleton robot

### D. Power Transmission

The gear drives are used to transmit the power for each joint. A spur gear pair (gear ratio-1:3) is used to transmit the power for the pronation/supination motion. The lager gear is attached to the inner hollow cylinder of the forearm cover by removing the cylindrical piece of material to obtain a hole. Bevel gear pairs (gear ratio-1:2) are used to transmit the power for the wrist ulnar/radial deviation and flexion/extension motions. Modules of each gear pairs are selected to obtain minimum backlash.

### E. Safety Aspects

The stoppers are attached for each motion to prevent the exceeding of the movable range for safety. The stoppers for pronation/supination motion are shown in Fig. 4. The robot does not have any sharp edges in its mechanical construction and mechanical stoppers. In addition, the maximum torque of the exoskeleton robot is limited by the software. Furthermore, each motor has an individual switch and there is an emergency stop switch beside the exoskeleton robot.

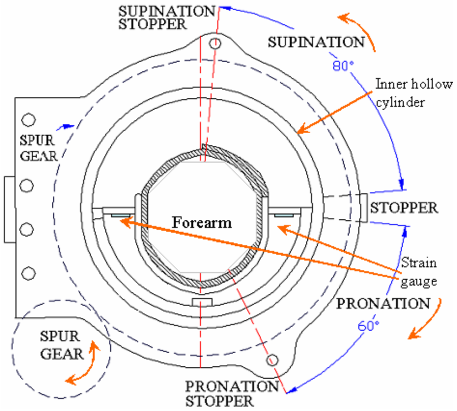


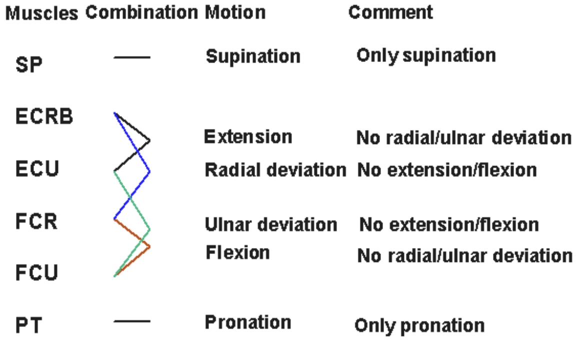
Fig. 4. Forearm cover - Front view

## III. CONTROLLER

The proposed exoskeleton robot is controlled based on the EMG signals and the hand force/forearm torque. In the proposed control method, the motion assist is carried out based on the hand force/forearm torque when the amount of the EMG activity levels is low. By applying sensor fusion with the EMG signals and the hand force/forearm torque, 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 [1][3][4].

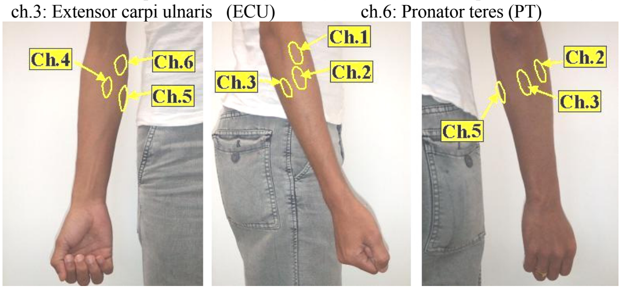
Since the forearm consists of many kinds of muscles, which are involved in finger, forearm pronation/supination motion, and elbow motion as well as wrist motion, it is not very easy to predict the wrist motion intention of the user based on the EMG signals of the muscles involved in wrist motion. In this study, 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 wrist flexion motion is generated by the muscles of flexor carpi radialis, flexor carpi ulnaris and palmaris longus (weak flexor), extension is generated by extensor carpi radialis longus, extensor carpi radialis brevis and extensor carpi ulnaris, wrist ulnar deviation is generated by muscles of flexor carpi ulnaris and extensor carpi ulnaris, and wrist radial deviation is generated by muscles of extensor carpi radialis longus, extensor carpi radialis brevis and flexor carpi radialis. Furthermore, the muscles of pronater quadratus and pronator teres generate forearm pronation and muscles of supinator and biceps brachii (long head) generates forearm supination. Some of the muscles for above motions are overlapped from other muscles. In the proposed controller, muscles and locations of each muscle's electrodes were selected to eliminate the ill-effect of muscles overlapping and to separate each motion easily. The selection of muscles to separate each motion is shown in TABLE 3. Surface anatomy of each muscle is studied and the location where only the desired muscle is exposed to skin is selected as the location of the electrode of the particular muscle. Six kinds of EMG signals (ch1: supinator, ch2: extensor carpi radialis brevis, ch3: extensor carpi ulnaris ch.4: flexor carpi radialis, ch.5: flexor carpi ulnaris, ch6: pronator teres) are measured to control the wrist flexion/extension motion, ulnar/radial deviation, and forearm supination/pronation motion as shown in Fig. 5. Two of the channels (ch.4: flexor carpi radialis, ch.5: flexor carpi ulnaris) are used to figure out the wrist flexion motion, other two of them (ch.2: extensor carpi radialis brevis, ch.3: extensor carpi ulnaris) are used to figure out the wrist extension motion, two of them (ch.3: extensor carpi ulnaris, ch.5: flexor carpi ulnaris) are used to figure out wrist ulnar deviation and other two of them (ch.2: extensor carpi radialis brevis, ch.4: flexor carpi radialis) are used to figure out wrist radial deviation.

TABLE 3 MUSCLE SELECTION



| Muscles | Combination | Motion | Comment |
|---|---|---|---|
| SP | — | Supination | Only supination |
| ECRB | | Extension | No radial/ulnar deviation |
| ECU | | Radial deviation | No extension/flexion |
| FCR | | Ulnar deviation | No extension/flexion |
| FCU | | Flexion | No radial/ulnar deviation |
| PT | — | Pronation | Only pronation |

ch.1: Supinator (SP)
ch.2: Extensor carpi radialis brevis (ECRB)
ch.3: Extensor carpi ulnaris (ECU)
ch.4: Flexor carpi radialis (FCR)
ch.5: Flexor carpi ulnaris (FCU)
ch.6: Pronator teres (PT)



(a) Front view (b) Side view (c) Rear view

Fig. 5. Location of electrodes

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, Root Mean Square (RMS) has been applied as the feature extraction method of the EMG levels for the fuzzy controller.

TABLE 4 FUZZY RULES

| Motion | IF | THEN |
|---|---|---|
| Supination | Ch1 = ZO | T1= ZO |
| | Ch1 = PS | T1= PS |
| | Ch1 = PB | T1= PB |
| | Ch1! = PB and Fx! = ZO and T = PS | T1= PS |
| | Ch1! = PB and Fx! = ZO and T = PB | T1= PB |
| Pronation | Ch6 = ZO | T1= ZO |
| | Ch6 = PS | T1= NS |
| | Ch6 = PB | T1= NB |
| | Ch6! = PB and Fx! = ZO and T = NS | T1= NS |
| | Ch6! = PB and Fx! = ZO and T = NB | T1= NB |
| Flexion | Ch4 = ZO and Ch5 = ZO OR CH5=PS OR Ch5=PB | T2= ZO |
| | Ch4 = PS and Ch5 = ZO | T2= ZO |
| | Ch4 = PS and Ch5 = PS | T2= NS |
| | Ch4 = PS and Ch5 = PB | T2= NS |
| | Ch4 = PB and Ch5 = ZO | T2= ZO |
| | Ch4 = PB and Ch5 = PS | T2= NS |
| | Ch4 = PB and Ch5 = PB | T2= NB |
| | Ch4! = PB and T = ZO and Fx=NS | T2= NS |
| | Ch4!= PB and T = ZO and Fx=NB | T2= NS |
| Extension | Ch2 = ZO and Ch3 = ZO OR CH3=PS OR Ch3=PB | T2= ZO |
| | Ch2 = PS and Ch3 = ZO | T2= ZO |
| | Ch2 = PS and Ch3 = PS | T2= PS |
| | Ch2 = PS and Ch3 = PB | T2= PS |
| | Ch2 = PB and Ch3 = ZO | T2= ZO |
| | Ch2 = PB and Ch3 = PS | T2= PS |
| | Ch2 = PB and Ch3 = PB | T2= PB |
| | Ch2! = PB and T = ZO and Fx=PS | T2= PS |
| | Ch2! = PB and T = ZO and Fx=PB | T2= PS |
| Radial Deviation | Ch2 = ZO and Ch4 = ZO OR CH4=PS OR Ch4=PB | T3= ZO |
| | Ch2 = PS and Ch4 = ZO | T3= ZO |
| | Ch2 = PS and Ch4 = PS | T3= PS |
| | Ch2 = PS and Ch4 = PB | T3= PS |
| | Ch2 = PB and Ch4 = ZO | T3= ZO |
| | Ch2 = PB and Ch4 = PS | T3= PS |
| | Ch2 = PB and Ch4 = PB | T3= PB |
| | Ch2! = PB and T=ZO and Fz=NS | T3=PS |
| | Ch2! = PB and T=ZO and Fz=NB | T3=PS |
| Ulnar Deviation | Ch3 = ZO and Ch5 = ZO OR CH5=PS OR Ch5=PB | T3= ZO |
| | Ch3 = PS and Ch5 = ZO | T3= ZO |
| | Ch3 = PS and Ch5 = PS | T3= NS |
| | Ch3 = PS and Ch5 = PB | T3= NS |
| | Ch3 = PB and Ch5 = ZO | T3= ZO |
| | Ch3 = PB and Ch5 = PS | T3= NS |
| | Ch3 = PB and Ch5 = PB | T3= NB |
| | Ch3! = PB and T = ZO and Fz=PS | T3=NS |
| | Ch3! = PB and T = ZO and Fz=PB | T3=NS |

In the table;
$Ch_i$- Channel $i$, $i$ =1, 2, 3, 4
$F_j$=Force sensor signal for axis $j$, $j$ =x,y,z
T=Torque sensor signal
$T_k$ =Torque command for motor $k$, $k$=1, 2, 3

The equation of RMS is written as:

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N} v_i^2} \qquad (1)$$

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 frequency is 2 kHz in this study.

The input variables for the controller are RMSs of six kinds of the EMG signals and the generated hand force/ forearm torque measured by the force/torque sensors. In the control rules, it was considered the generated hand force/ forearm torque are 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) [1] [3] [4]. In other words, the exoskeleton robot is controlled based on the generated hand force/forearm torque 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 robot can be controlled in accordance with the human user's intention. By applying sensor fusion with the EMG signals and the generated hand force, error motion caused by little EMG levels and the external force affecting to human arm can be avoided. The signal flow diagram is shown in Fig.6.

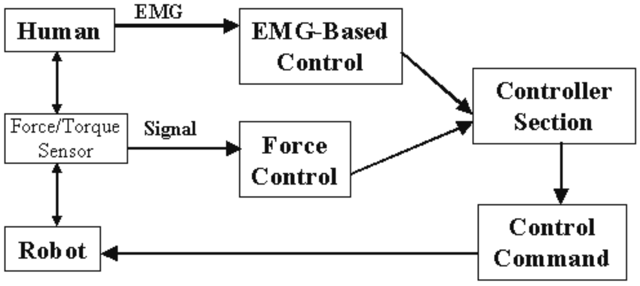


Fig. 6. Signal flow diagram

When the robot's user activates the muscles, fuzzy control is performed based on RMSs of six kinds of the EMG signals. Three kinds of linguistic variables (ZO: Zero, PS: Positive Small, and PB: Positive Big) are prepared for each RMS and five kinds of linguistic variables (NB: Negative Big, NS: Negative Small ZO: Zero, PS: Positive Small, and PB: Positive Big) are prepared for each force/torque signals and torque commands. Fuzzy IF-THEN control rules have been designed based on experiment which was performed to find out the patterns of EMG signals for the motion of forearm and wrist. In the experiment, EMG patterns have been identified for different motion and different torque of wrist and forearm. Then rules are designed to provide torque command according to the EMG activity level. The rules are to generate the wrist flexion/extension motion based on RMSs of four kinds of the EMG signals and the wrist ulnar/radial deviation motion based on RMSs of four kinds of EMG signals. In this study 46 kinds of fuzzy IF-THEN rules are defined for the controller. Those are shown in TABLE 4.

When the exoskeleton's user does not activate the muscles so much for wrist and forearm motions, force control of the hand-force/forearm-torque is performed to make the force/torque sensor signals become zero in order to prevent the exoskeleton from disturbing the user's motion.

## IV. EXPERIMENT

The experiments have been performed with healthy male subjects (Subject A-28 years and subject B -26 old) to prove the effectiveness of the proposed exoskeleton robot. The experimental setup is shown in Fig. 7. It consists of the robot and human subject, three motors with encoders, a personal computer (PC) with an interface card (JIF-171-1), an EMG amplifier, a strain amplifier, two motor drivers (each has two channels) and power suppliers. Amplified EMG and force/torque sensors signals are send to PC via interface card. In the PC, controller calculates the required torque commands. They have been applied to the motor drivers. Motor drivers actuate the motors according to the given torque commands. The rotations of the motors are measured from the encoders and fed back to PC via the interface card.

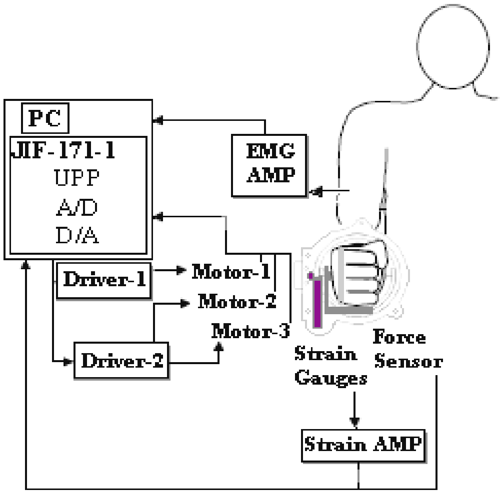
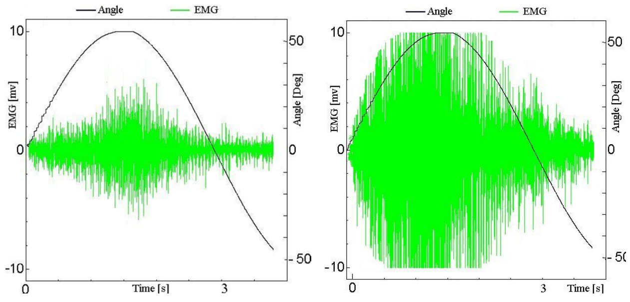


Fig. 7. Experimental setup

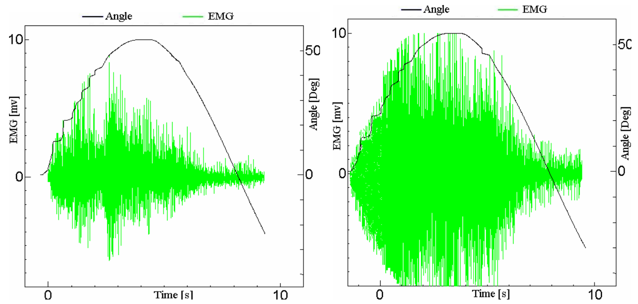
In the experiment, wrist and forearm motions were performed with and without assist of the robot. When the human subject performed motions without assist of the robot, the force control is applied to cancel out the force between the robot and the user (i.e. not to disturb the user's motion). In the first experiment, the subjects performed wrist extension/ flexion motion. The activation levels of the muscle of extensor carpi radialis brevis (ECRB) of subject-A with and without the assist of exoskeleton are shown in Fig. 8. From the activation levels of ECRB it can be clearly seen that the activation levels decreased, when the exoskeleton robot assisted the motion. The experimental results of subject-B for forearm pronation/supination motion and combined motions of forearm pronation and wrist ulnar deviation are shown in Fig. 9 and Fig. 10, respectively. From the experimental results one can clearly see that the motions are smooth and the muscles activation levels decrease when the exoskeleton robot assisted the motions.



(a) With assist

(b) Without assist

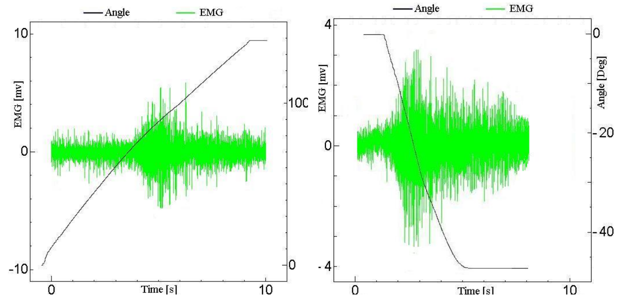
Fig. 8. Muscles activation level for wrist extension/flexion



With assist

Without assist

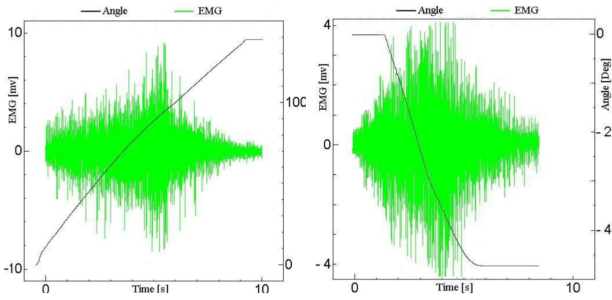
Fig. 9. Results for the motion of forearm pronation/supination (**ch 6**)



PT (**ch 6**)

FCU (**ch 5**)

(a) With assist



PT (**ch 6**)

FCU (**ch 5**)

(b) Without assist

Fig. 10. Combined motions of forearm pronation and wrist ulnar deviation

## V. CONCLUSION

A 3 DOF exoskeleton robot and its control system based on skin surface EMG signals were proposed to assist wrist and forearm motion of physically weak individuals. The exoskeleton robot generates the smooth natural motions of forearm pronation/supination, wrist flexion/extension and ulnar/radial deviation, and daily motions in accordance with user's motion intention. The robot is convenient to use for assisting human forearm and wrist motions. The experiments showed the effectiveness of the exoskeleton robot to assist wrist and forearm motions.

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