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SUEFUL-7: A 7DOF Upper-Limb Exoskeleton Robot with Muscle-Model-Oriented EMG-Based Control

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Abstract—**This paper proposes an electromyography (EMG) signal based control method for a seven degrees of freedom (7DOF) upper-limb motion assist exoskeleton robot (SUEFUL-7). The SUEFUL-7 is able to assist the motions of shoulder vertical and horizontal flexion/extension, shoulder internal/external rotation, elbow flexion/extension, forearm supination/pronation, wrist flexion/extension, and wrist radial/ulnar deviation of physically weak individuals. In the proposed control method, an impedance controller is applied to the muscle-model-oriented control method by considering the end effecter force vector. Impedance parameters are adjusted in real time by considering the upper-limb posture and EMG activity levels. Experiments have been performed to evaluate the effectiveness of the proposed robotic system.**

I. INTRODUCTION

RECENT society faces the problem of taking care of physically weak people such as the elderly, injured and/or handicapped. This problem is increasingly significant as the elderly population and cost of case increases. Assistive robotic technology can play an important role in rehabilitation and motion assist of physically weak persons. An exoskeleton robot is one of the assistive robots which are able to assist the limb motions of physically weak individuals. Upper-limb motions are very important to perform daily activities. Therefore, many upper-limb exoskeleton robots and their control methods [1]-[8] have been developed to assist human upper-limb motions. This paper proposes an electromyography (EMG) signal based control method for a seven degrees of freedom (7DOF) upper-limb motion assist exoskeleton robot (SUEFUL-7). The SUEFUL-7 is able to assist the daily motions of shoulder vertical and horizontal flexion/extension, shoulder internal/external rotation, elbow flexion/extension, forearm supination/pronation, wrist flexion/extension, and wrist radial/ulnar deviation of physically weak individuals. The axes offset of wrist joint [5] and the moving center of rotation (CR) of shoulder joint [6] are applied in the hardware design of the SUEFUL-7. The slight axes offset of wrist is important for the wrist joint of the exoskeleton robot to avoid the undesired pain for users, since wrist joint is high sensitive to changes in position and torque [1]. The moving center of rotation (CR) of shoulder joint of the exoskeleton robot should be considered in order to cancel out the ill effects caused by the position difference between the CR of the robot shoulder and the human shoulder [6].

The electromyography (EMG) signals of human muscles can be used as input information to control robotic systems [8], [9], since the EMG signals are related to the motion intention of the human user. The amplitude of the EMG signals reflects the muscles activity levels. Therefore, they can be used to predict the motion intentions of the user in real time. Although intramuscular EMG signals give better muscle activation pattern than that of the skin surface EMG signals, they are difficult to use practically, since skin inversion is necessary. Therefore, the skin surface EMG signals of the upper-limb muscles of the exoskeleton's user are used as main input information to control the SUEFUL-7. Real time control is able to be realized for the physically weak persons without manipulating any equipment by applying the skin surface EMG signals as main input signals to the controller. The EMG-based fuzzy-neuro control method has been shown to be one of the most effective control methods to control exoskeleton robots in previous studies [6], [7]. However, the control rules become complicated if the number of degrees of freedom of the exoskeleton robot is increased. Therefore, a muscle-model-oriented control method has been proposed [8]. However, since a human can moderately control the upper-limb impedance [11], the controller of the SUEFUL-7 should have the ability to control upper-limb impedance to generate human upper-limb like motion. Therefore, in the proposed control method an impedance controller is applied to the muscle-model-oriented control method considering the hand force vector (*i.e.,* hand motion vector). Impedance parameters are adjusted in real time as a function of the upper-limb posture and EMG activity levels.

II. HARDWARE DESIGN OF THE SUEFUL-7

A. Requirements of an Upper-Limb Exoskeleton Robot

The exoskeleton robot should include the axes deviation of wrist flexion/extension axis and wrist radial/ulnar axis. Movement of the center of rotation of shoulder joint according to the upper-arm motions must be considered to cancel out the ill effect caused by that in design. If the exoskeleton has to be attached to both forearm and upper-arm of the user, then the mechanism that allows the moving of the center of rotation of the shoulder joint must be considered [6] in the upper-limb exoskeleton robot. This mechanism reduces the ill effects caused by the position difference between the center of rotation of the robot shoulder and the human shoulder. The links, cables, pulleys, other mechanical components and motors of the exoskeleton robot should be

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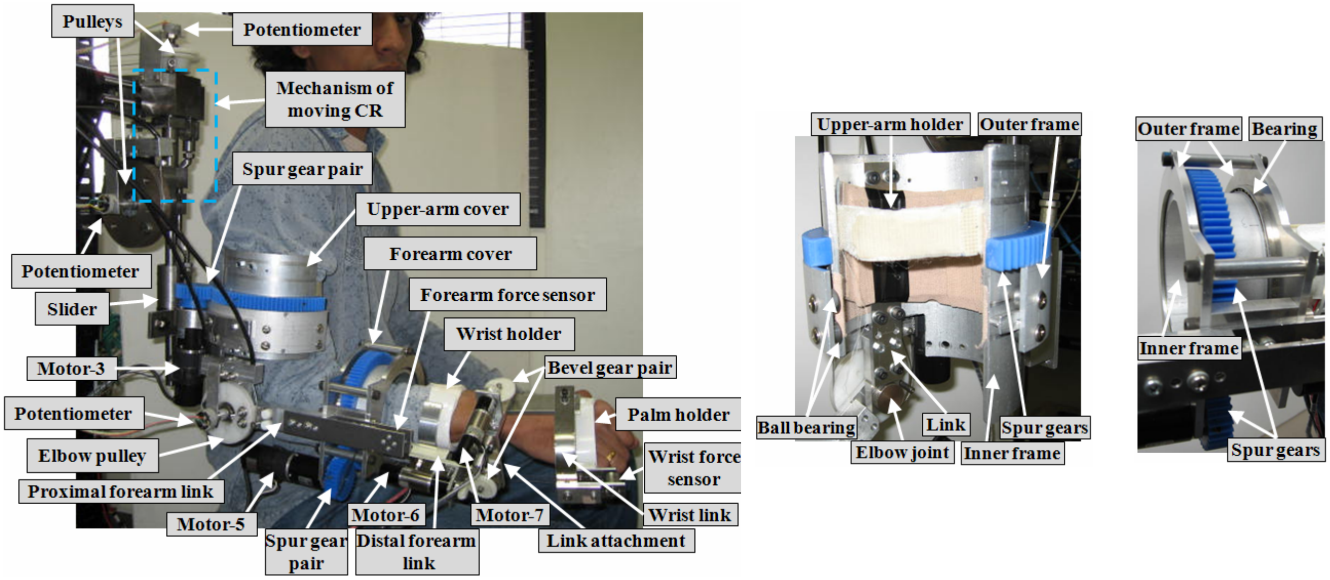


(a) Overall System (b) Upper-arm cover (c) Forearm cover

Fig. 1. SUEFUL-7: 7DOF upper-limb motion assist exoskeleton robot

located to eliminate interference during upper-limb motion of the robot and the user. Moreover, the mechanical singularity should not occur within the workspace of the robot. As the upper-limb exoskeleton robots also directly interact with the human user, safety is the highest priority.

B. Design of the SUEFUL-7

The SUEFUL-7 was designed to be worn on the right upper-limb as shown in Fig. 1. The weight of the SUEFUL-7 is about 5Kg. Considering that most physically weak persons use wheel chairs, the SUEFUL-7 was designed so that it could be installed on a wheel chair. Therefore, the user does not feel the weight of the robot. The SUEFUL-7 consists of shoulder motion, elbow motion, forearm motion and wrist motion support parts. The shoulder motion support part of the SUEFUL-7 consists of an upper-arm cover, driver and driven pulleys (for shoulder horizontal and vertical flexion/extension motions), a motor, a spur gear pair, potentiometers, a slider and the mechanism for moving CR [6]. In order to generate shoulder vertical and horizontal flexion/extension motion, motor pulleys act as driver pulleys and pulleys connected to the shoulder joint act as driven pulleys. The motors for the shoulder horizontal and vertical flexion/extension motions have been fixed in separate locations on the frame of the robot. Motor-1 and motor-2 are the motors for the shoulder horizontal and vertical flexion/extension motions, respectively. The rotational motions generated in the motors are transferred to the shoulder by pulleys and cable drives. The arm holder is fixed to inner frame of the upper-arm cover as shown in Fig. 1(b). The arm holder is made of thin flexible plastic with a fabric hook-and-loop fastener (*i.e.,* magic tape, Velcro) to hold the user's upper-arm. The distance between the arm holder and the CR of the shoulder joint of the exoskeleton is adjusted automatically by a slider mechanism, in accordance with the shoulder motion, in order to cancel out the ill effects caused by the position difference between the CR of the robot shoulder and the human shoulder [6]. Details of mechanism of CR and activation of slider and upper-arm links can be referred in [6]. The outer frame of the upper-arm cover is connected to the slider as shown in Fig. 1(a). The outer frame and the inner frame of the upper-arm cover are assembled using arrays of ball bearings as shown in Fig. 1(b) so that inner frame can rotate with respect to the outer frame. The rotation of the inner frame generates the internal/external rotation of shoulder. The upper-arm can be inserted to the exoskeleton through the opening in the side. Motor-3 is connected to outer frame of the upper-arm cover as shown in Fig. 1(a). The shaft of motor-3 is attached to a spur gear pinion which is meshed with spur gear wheel attached to the inner frame of the upper-arm cover. The rotation of the motor is transferred to the inner frame of upper-arm via the gear pair. The inner frame of the upper-arm cover is attached to the elbow joint using a link as shown in Fig. 1(b).

The 1DOF elbow motion assist part of the exoskeleton robot consists of the proximal forearm link, a pulley, and a potentiometer. Motor-4 drives a pulley to generate elbow flexion/extension motion and is fixed in a separate location on the frame of the robot. The rotational motion generated in the motor-4 is transferred to the elbow pulleys of the SUEFUL-7 through a cable drive.

The forearm motion support part consists of the forearm cover, the distal forearm link, a DC motor, forearm force sensor, a wrist holder, and strain gauges. The motor for supination/pronation motion, motor-5, is attached to the outer housing of the forearm cover. The rotational motion generated from the motor is transferred to the inner frame of the forearm cover through a spur gear pair. The outer frame of the forearm cover and the inner frame are assembled through two bearings [see Fig. 1(c)] in such a way that the forearm can be inserted into the hole of the hollow cylinder. The inner frame of the forearm cover rotates with respect to the fixed outer frame to generate forearm supination/ pronation motion. The proximal forearm link is attached to the outer frame of the forearm cover through the forearm force sensor as shown in Fig. 1(a). The distal forearm link is attached to the inner frame of the forearm cover and the wrist holder. The wrist holder can be worn on the forearm of the user. Since the distal forearm link is attached to the inner frame of forearm cover, the wrist holder rotates with the rotating inner frame. There by the forearm is rotated to generate supination/pronation motion.

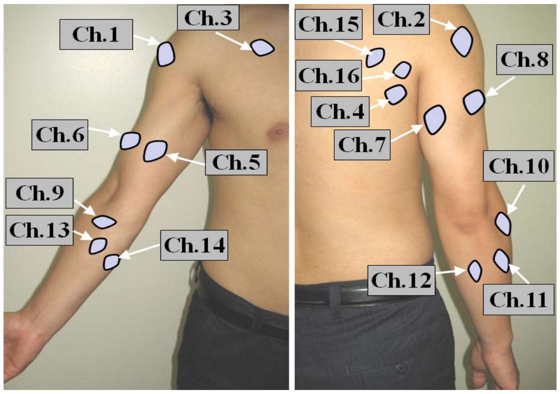
The wrist motion support part consists of a link attachment, two DC motors, two drive and driven bevel gear pairs, a palm holder, a wrist force sensor and a wrist link which connects the palm holder and the link attachment. The motor for wrist flexion/extension motion, motor-6, is fixed on the distal forearm link. The rotational motion generated in the motor-6 is transferred to the wrist flexion/extension axis through a bevel gear pair as shown in Fig. 1(a). The distal forearm link is attached with an L-shaped link attachment using a thrust bearing, a ball bearing and a stepped shaft to form a revolute joint. The link attachment rotates with respect to the distal forearm link. The rotation of link attachment generates the wrist flexion/extension motion which is transferred to the users hand by the palm holder. Motor-7 is attached to the link attachment for the wrist radial/ulnar deviation. The rotational motion generated in the motor-7 is transferred to the wrist radial/ulnar axis through a bevel gear pair. The wrist link is attached to the link attachment using a thrust bearing, a ball bearing and a stepped shaft to form a revolute joint. The wrist link rotates with respect to the link attachment. The rotation of wrist link generates the wrist radial/ulnar deviation motion and which is transferred to the users hand by the palm holder. The palm holder and the wrist force sensor are attached to the wrist link. The link attachment has been designed to provide the axes deviation of the radial/ulnar axis and the flexion/extension axis [6].

For safety mechanical stopper prevent the exoskeleton from exceeding anatomical joint limits. Each motor and motor driver has an individual switch and there is an emergency stop switch on the SUEFUL-7 in easily accessible location for the left arm of the user. In addition, the maximum torque and maximum velocity of the exoskeleton robot are limited by the software to prevent sudden unexpected motion.

III. EMG-BASED CONTROL METHOD

A. The controller

ch.1: Deltoid-anterior
ch.2: Deltoid-posterior
ch.3: Pectoralis major-clavicular
ch.4: Teres major
ch.5: Biceps-short head
ch.6: Biceps-long head
ch.7: Triceps-long head
ch.8: Triceps-lateral head
ch.9: Pronator teres
ch.10: Supinator
ch.11:Extensor carpi radialis brevis
ch.12: Extensor carpi ulnaris
ch.13: Flexor carpi radialis
ch.14: Flexor carpi ulnaris
ch.15: Infraspinatus
ch.16: Teres minor



(a) Front view (b) Rear view

Fig. 2. Locations of monitored muscles

The SUEFUL-7 is controlled by using the EMG signals of the user as the primary input information and is used to determine the user's motion intention. The forearm force (*i.e.*, generated force between the robot and the forearm of the user), the hand force (*i.e.*, generated force between the robot and the hand of the user) and forearm torque (*i.e.*, generated torque between the wrist holder of the robot and the forearm of the user) are used as subordinate input information for the controller. When the user EMG signal level is low the forearm force/torque and hand force are used to control the SUEFUL-7 as in [6], [7]. When the user EMG signal level is high, EMG signals are used to control the SUEFUL-7 as in [6], [7]. When the user's muscle activation level is medium combination of EMG signal, forearm force/torque and hand force are used to control the robot as in [6], [7].

In order to identify the 7DOF motions the EMG signals of sixteen locations are measured with electrodes [NE-101A, Nihon Koden Co.] through an amplifier [MEG-6108, Nihon Koden Co.], each location relating a muscles (deltoid-anterior, deltoid-posterior, pectoralis major-clavicular, teres major, biceps-short head, biceps-long head, triceps-long head, triceps-lateral head, pronator teres, supinator, extensor carpi radialis brevis, extensor carpi ulnaris, flexor carpi radialis and flexor carpi ulnaris, Infraspinatus, Teres minor). The locations of electrodes are shown in Fig. 2. The shoulder vertical motion is activated by agonist muscles of deltoid-anterior and teres major. Agonist muscles of deltoid-posterior and pectoralis major activate human shoulder horizontal motion. Shoulder rotation motion is activated by infraspinatus and teres minor. The human elbow motion activates by two agonist muscles of biceps and triceps. Wrist flexion/extension motion and radial ulnar deviation is activates by the agonist muscles of extensor carpi radialis brevis and flexor carpi radialis, and extensor carpi ulnaris and flexor carpi ulnaris, respectively.

In order to extract the features of the raw EMG signal, the RMS is calculated and used as an input signal for the controller. In this study, the number of samples and the sampling frequency are set to be 100 and 2 kHz, respectively in RMS calculation. The relationship between the sixteen EMG RMSs and the joint torques for the 7DOF upper-limb motion can be written as (1) if the posture of the upper-limb does not affect the relationship.

$$\tau = \begin{bmatrix} \tau_{sv} \\ \tau_{sh} \\ \tau_{sie} \\ \tau_{e} \\ \tau_{f} \\ \tau_{wf} \\ \tau_{wr} \end{bmatrix} = \begin{bmatrix} w_{sv1} & w_{sv2} & .... & w_{sv15} & w_{sv16} \\ w_{sh1} & w_{sh2} & .... & w_{sh15} & w_{sh16} \\ w_{sie1} & w_{sie2} & .... & w_{sie15} & w_{sie16} \\ w_{e1} & w_{e2} & .... & w_{e15} & w_{e16} \\ w_{f1} & w_{f2} & .... & w_{f15} & w_{f16} \\ w_{wf1} & w_{wf2} & .... & w_{wf15} & w_{wf16} \\ w_{wr1} & w_{wr2} & .... & w_{wr15} & w_{wr16} \end{bmatrix} \begin{bmatrix} CH1 \\ CH2 \\ CH3 \\ . \\ . \\ CH15 \\ CH16 \end{bmatrix} \tag{1}$$

where τ, τ_{sv}, τ_{sh}, τ_{sie}, τ_e, τ_f, τ_{wf} and τ_{wr} are the joint torque vectors for, shoulder vertical and horizontal flexion/extension, shoulder internal/external rotation, elbow flexion/extension, forearm supination/pronation, wrist flexion/extension and wrist radial/ulnar deviation, respectively. *CH*n is the RMS value of the EMG signal measured in channel *n*, w_{svn} is the weight for *n*th EMG to estimate the torque for shoulder vertical flexion/extension motion, w_{shn} is the weight for *n*th EMG to estimate the torque for shoulder horizontal flexion/extension motion, w_{sien} is the weight for *n*th EMG to estimate the torque for shoulder internal/external rotation motion, w_{en} is the weight for *n*th EMG to estimate the torque for elbow flexion/extension motion, w_{fn} is the weight for *n*th EMG to estimate the torque for forearm supination/pronation motion, w_{wfn} is the weight for *n*th EMG to estimate the torque for wrist flexion/extension motion and w_{wrn} is the weight for *n*th EMG to estimate the torque for wrist radial/ulnar deviation. Since weights of (1) can be defined using the knowledge of human upper-limb anatomy or the results of experiments, the desired joint torque vector generated by muscle force can be calculated if every weight for the EMG signals is properly defined.

The posture of the upper-limb affects the relationship between the EMG signals and the generated joint torques because of anatomical reasons such as change of the moment arm. Therefore, the effect of the posture difference of the upper-limb must be taken into account to estimate the correct joint torque.

The calculated joint torque vector of the user is transferred to the end effecter force vector of the user using (2).

$$F_{end} = J^{-T}\tau \tag{2}$$

$$F_{Avg} = \frac{1}{N}\sum_{i=1}^{N} F_{end}(i) \tag{3}$$

$$\ddot{X}_d = F_{Avg} M^{-1} \tag{4}$$

where F_{end} is the end effecter force vector, J is the Jacobian matrix, τ is the joint torque vector, F_{Avg} is average force vector of F_{end} in N number of samples, $\ddot{X}_d$ is desired end effecter acceleration vector and M weight of the upper-arm and robot. The following impedance control equation is used to resultant end effecter force vector.

$$F = M\ddot{X}_d + B\left(\dot{X}_d - \dot{X}\right) + K\left(X_d - X\right) + f \tag{5}$$

where F is the resultant end effecter force vector, B is the viscous coefficient, K is the spring coefficient, $\dot{X}$ is the calculated end effecter velocity using measured joints' angles and f is the external force which is zero if there is no external load. Estimation of the properties of upper limb joint impedance (B and K) is explained in next subsection.

$$\tau_{motor} = J^T F \tag{6}$$

where τ_{motor} is the calculated joint torque command vector. The calculated joint torque command vector of the user is multiplied by the power-assist rate and then transferred to the torque command of the driving motor.

B. Estimation of impedance parameters

Impedance parameters (B and K) in (5) depend on the upper-limb posture and activity levels of activated upper-limb muscles. Therefore, impedance parameters have to be adjusted online in the controller. Following function is proposed to adjust the impedance parameters.

$$B = B_0 m_B l_B \tag{7}$$

$$K = K_0 m_K l_K \tag{8}$$

where B, B_0, m_B, and l_B are the adjusted viscous coefficient, initial viscous coefficient for initial position when EMG levels of muscles used to estimate impedance are in defined level, effect from EMG, and effect from posture respectively. K, K_0, m_K, and l_K are adjusted spring coefficient, initial spring coefficient for initial position when EMG levels of muscles used to estimate impedance are in defined level, effect from EMG, and effect from posture respectively.

$$m_B = \lambda_B \times ch_6 \times ch_8 \tag{9}$$

$$l_K = \lambda_K \times ch_6 \times ch_8 \tag{10}$$

where λ_B and λ_K are coefficients of the EMG effect. ch_6, and ch_8, are RMS values of biceps long head and triceps lateral head, respectively. Since the effect of posture change is nonlinear and stochastic, fuzzy reasoning is applied to estimate the effect of posture change. Three fuzzy linguistic variables (*NE*: negative, *ZO1*: zero, and *PO*: positive) have been defined for the distance along Cartesian axis x. Another three fuzzy linguistic variables (*ZO*: zero, and *PS*: positive small, and *PB*: positive big) have been defined for viscous coefficient and spring coefficient through each axis, and distance along y axis. Sigmoid function has been used as membership function for *NE*, *PO*, *ZO,* and *PB* and where as Gaussian function has been used as membership function for *ZO1* and *PS*. Fuzzy if-then rules have been defined by using results of other researches [12]-[16] and considering the tendency of impedance parameter change with the posture.

C. Muscle-Model Matrix Modification

A neuro-fuzzy modifier is applied to modify the muscle-model matrix to take into account the effect of the upper-limb posture difference of the user [8]. The neuro-fuzzy modifier is used to adjust the weight matrix in (1) by multiplying the coefficients in accordance with the upper-limb posture of the user, so that the effect of upper-limb posture difference can be compensated, effectively. Adaptation of the muscle-model-oriented controller itself to each person is also performed by adjusting the weight matrix of (1). Architecture of the neuro-

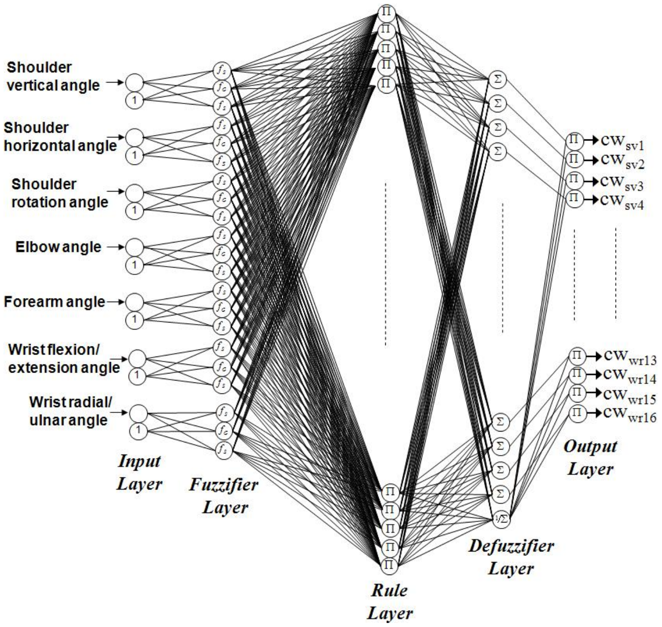


Fig. 3. Architecture of the neuro-fuzzy modifier

fuzzy modifier is shown in Fig. 3. Here, Σ is sum of the inputs and Π is multiplication of the inputs. The architecture of the neuro-fuzzy modifier is the same as a neural network and it consists of five layers (input layer, fuzzifier layer, rule layer, defuzzifier layer, and output layer). Seven joint angles of shoulder, elbow, forearm and wrist are used as input information to the neuro-fuzzy modifier. Each joint angle is divided into three regions. The output from the neuro-fuzzy modifier is the coefficient for each weight of muscle-model matrix in (1). Consequently, the weight matrix in (1) is adjusted online by the neuro-fuzzy modifier according to the user's upper-limb posture at every sampling time. In the fuzzifier layer, the degree of fitness of each joint angle is sent to the rule layer. Two kinds of nonlinear functions (f_G: Gaussian function and f_S: Sigmoid function) are used to express the membership of the neuro-fuzzy modifier [8]. The rules for every combination of the joint angle are prepared in the rule layer. Initial weight for each rule is set to be 1, so that the coefficient for every weight in (1) is 1.0 in the beginning.

The online adaptation of the neuro-fuzzy modifier itself to each user is important if one exoskeleton robot is used by multiple users. Therefore, the neuro-fuzzy modifier is trained to adapt itself to each user using the information of the forearm force/torque sensors and wrist force sensor. The output of the neuro-fuzzy modifier is 1 for every component of the muscle-model matrix in the beginning. The error-back propagation learning algorithm is applied to minimize the squared error functions, in order to eliminate the error of the muscle-model-matrix.

$$E = \frac{1}{2} f_{fs1}^2 \qquad (11)$$

$$E = \frac{1}{2} f_{fs2}^2 \qquad (12)$$

$$E = \frac{1}{2}\left[f_{fs3} - f_{fs1} \right]^2 \qquad (13)$$

where f_{fs1} is the measured forearm force vector in the moving direction obtained from forearm force sensor, f_{fs2} is the measured forearm torque obtained from forearm torque sensors and f_{fs3} is the measured wrist force vector in the moving direction obtained from wrist force sensor. The error function of the forearm force vector (11) of the user is transferred to shoulder and elbow joints using the Jacobian matrix. The error function of the forearm torque vector (12) is used to train forearm supination/pronation motion. The error function of the vector of the wrist and forearm force deference (13) of the user is transferred to wrist flexion/ extension and radial/ulnar joints using the Jacobian matrix.

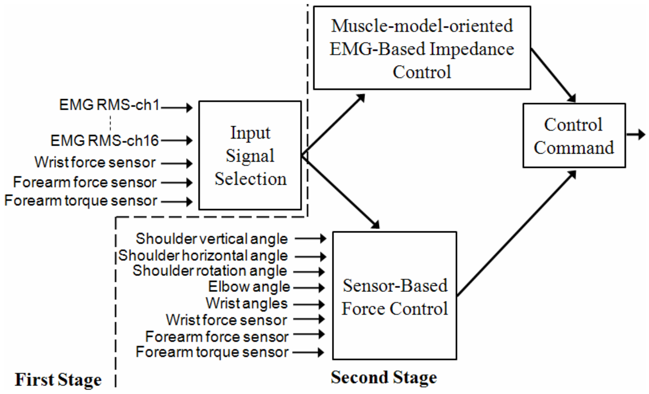


Fig. 4. Structure of the controller

D. Structure of the controller

The overall structure of the controller is depicted in Fig. 4. The controller consists of two stages: first stage-input signal selection, second stage- muscle-model-oriented EMG-based impedance control. In the first stage of the controller, proper input information for the controller is selected in accordance with the user's muscle activity levels. The muscle-model-oriented EMG-based impedance control and/or sensor-based control are selected in this stage in accordance with the EMG RMS levels of the user's muscles (ch.1-ch.5, ch.7, ch.9-ch.11, ch.13- ch.16). When the user activates his/her muscles, muscle-model-oriented EMG-based control is selected. In the second stage muscle-model-oriented EMG-based control (explained in section III *A*) and/or sensor-based control is performed to control the SUEFUL-7.

IV. EXPERIMENT

The experimental set-up is depicted in Fig. 5. In the experiments, young male subjects performed the daily activities of upper-limb. In the first experiment subject-A performed cooperative motions of upper-limb to show the effectiveness of neuro-fuzzy modifier. The activity level of muscles is supposed to be reduced to generate the similar motion, if the neuro-fuzzy modifier is properly trained and power-assist is properly performed. Figure 6 shows that the activity of biceps-short head muscle. It shows the activity level of biceps-short head is reduced after the adaptation of neuro-fuzzy modifier. In the second experiment, subject-A and B performed upper-limb motions with and without assistance of the SUEFUL-7 to show the effectiveness of power-assist. The EMG levels of the related muscles were measured for both cases. If the SUEFUL-7 assists the motions properly, EMG levels of related muscles should be reduced, when the robot assists the same motions. The experimental

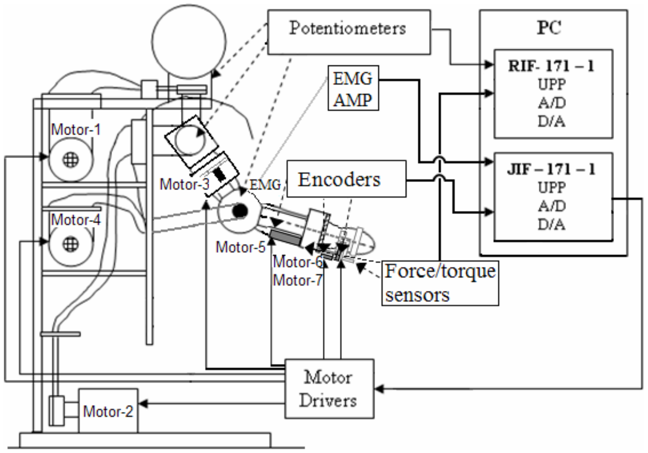
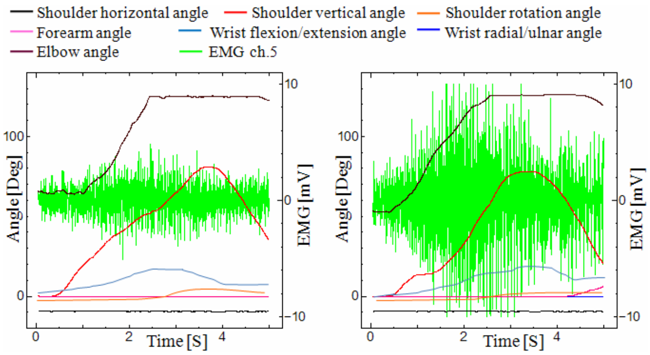
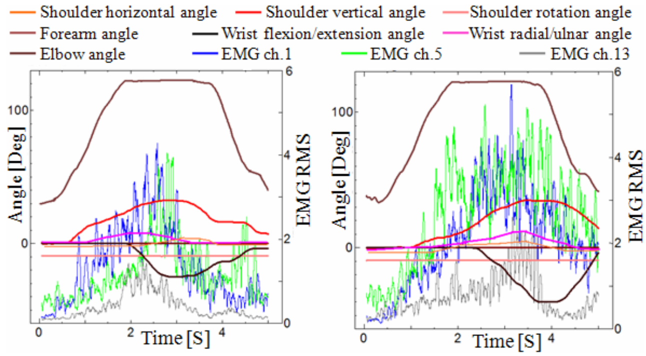


Fig. 5. Experimental set-up



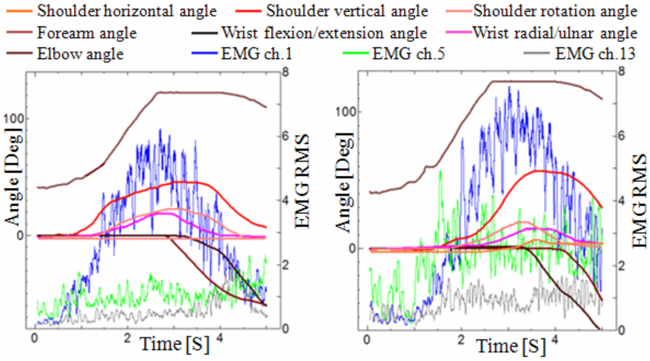
(a) After adaptation (b) Before adaptation

Fig. 6 Experimental result of subject-A



(a) with assist (b) without assist

Fig. 7 Experimental result of subject-A for drinking motion



(a) with assist (b) without assist

Fig. 8 Experimental result of subject-B for cooperate motion of upper-limb

results of subject-A for drinking motion is shown in Fig. 7. The experimental result shows that the EMG RMS levels have been reduced when the motion is assisted. From the results of subject-B (Fig. 8), similar effects are observed.

V. CONCLUSION

An EMG-based control method was proposed for a 7DOF upper-limb motion assist exoskeleton robot to assist the motions of shoulder vertical and horizontal flexion/extension, elbow flexion/extension, forearm supination/pronation, wrist flexion/extension, and wrist radial/ulnar deviation in daily activities of physically weak individuals. Proposed control method was applied impedance control to the muscle-model-oriented control method by considering hand force vector. Impedance parameters were adjusted in real time by considering upper-limb posture and EMG activity levels. The experimental results showed the effectiveness of the proposed robotic system.

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