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Upper-Limb Exoskeletons for Physically Weak Persons

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1. Introduction

Robotics technology is expected to play an important role not only in industries, but also in welfare and medicine. A power-assist exoskeleton, which is directly attached to the human body and assist the motion in accordance with the user's motion intension, is one of the most effective assist robots for the physically weak persons. A study of power-assist exoskeletons has been carried out for a long time (Mosher & Wendel, 1960). The power-assist exoskeletons, which are sometimes called as power suits, man amplifiers, man magnifiers, or power-assist systems, have been studied for the purpose of military, industry, or medial use (Cloud, 1965; Mosher, 1967; Vukobratovic, 1975; Kazerooni & Mahoney, 1991). Recently, many studies on power-assist robots have been carried out to help the motion of physically weak persons such as disabled, injured, and/or elderly persons in daily activities or rehabilitation (Nagai *et al.*, 1998, Kiguchi *et al.*, 2001-2007; Rosen *et al.*, 2001; Tsagarkis & Caldwell, 2003; Sasaki *et al.*, 2004).

EMG-based control (i.e., control based on the skin surface electromyogram (EMG) signals of the user) is often used for control of the robotic systems (Farry *et al.*, 1996; Suryanarayanan, 1996; Fukuda *et al.*, 2003) since EMG signals of user's muscles directly reflect the user's motion intension. When certain motion is performed, the EMG signals of the related muscles show the unique pattern. Therefore, upper-limb motion of the user could be predicted by monitoring EMG signals of certain muscles of the user since the amount of EMG signal is proportional to the activity level of the muscle. Consequently, the EMG-based control is good at automatically activating the power-assist exoskeletons in accordance with user's motion intention. However, the EMG-based control is not easy to be realized for multi-DOF power-assist exoskeletons because 1: obtaining the same EMG signals for the same motion is difficult even with the same person, 2: activity level of each muscle and the way of using each muscle for a certain motion is different between persons, 3: real time motion prediction is not easy since many muscles are involved in a joint motion, 4: one muscle is not only concerned with one motion but also another kinds of motion, 5: role of each muscle for a certain motion varies in accordance with joint angles (Dominici *et al.*, 2005), and 6: the activity level of some muscles such as bi-articular muscles are affected by

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the motion of the other joint. The most of the above mentioned problems can be cleared by applying neuro-fuzzy control (i.e., the combination of adaptive neuro control and flexible fuzzy control).

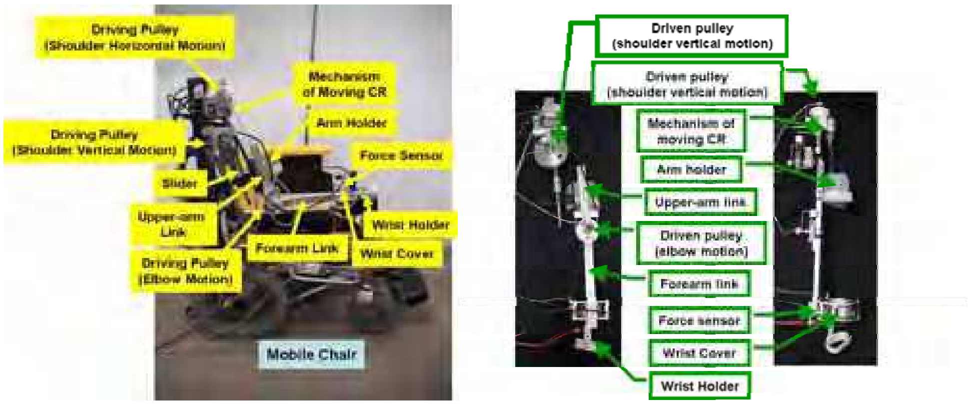
The design and control method of upper-limb exoskeletons are explained in this chapter. Four-DOF upper-limb power-assist exoskeletons are introduced as examples of effective exoskeletons.

2. Exoskeletons for Upper-Limb Assist

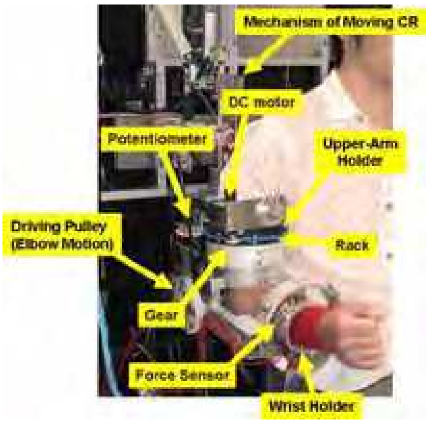
Assist of upper-limb motion is important in daily activities. Therefore, many kinds of upper-limb exoskeletons have been proposed up to the present (Kiguchi *et al.*, 2001-2007) in order to improve the quality of life of physically weak persons. In exoskeletons, it is not easy to locate actuators and links in appropriate positions since the user's body is usually placed in the center of the system. Furthermore, the actuators and links of the exoskeletons must be located not to prevent the user motion, although the position of the rotational center of the exoskeleton's joints must be the same as that of the user's joint. In the case of the elbow joint, the joint is modeled as a uniaxial hinge joint (London, 1981) although it consists of three bones (humerus, ulna, and radius). Therefore, it is not difficult to locate the axis of the rotational center of the exoskeleton's elbow joint to be the same as that of the user's elbow joint. In the case of the shoulder joint, however, it is not easy to locate the position of the rotational center of the exoskeleton's shoulder joint to be the same as that of the user's shoulder joint since the joint is modeled as a spherical joint (Kiguchi *et al.*, 2003a, 2003b, 2004, 2006a).

A 4DOF power-assist exoskeleton (Kiguchi *et al.*, 2006c), which assists shoulder vertical and horizontal flexion/extension motion, elbow flexion/extension motion, and forearm pronation/supination motion, is depicted in Fig. 1 (a) as an example of the upper-limb power-assist exoskeleton robot. It mainly consists of a shoulder motion assist mechanism, an elbow motion assist mechanism, a forearm motion assist mechanism, four DC motors, the shoulder mechanism of the moving center of rotation, and a wrist force sensor, and is installed on a mobile wheel chair. In this system, the mobile wheel chair itself is able to generate 2DOF motion.

Another 4DOF power-assist exoskeleton (Kiguchi *et al.*, 2006b), which assists shoulder 3DOF motion (vertical and horizontal flexion/extension, and internal/external rotation motion) and elbow flexion/extension motion, is shown in Fig. 1 (b) as another example of the upper-limb power assist exoskeleton. It mainly consists of four main links, an upper-arm holder, a wrist holder, four DC motors, the shoulder mechanism of the moving center of rotation, the mechanism for shoulder inner/outer rotation motion assist, an elbow joint, a wrist force sensor, and driving wires. The shoulder vertical/horizontal motion is assisted by controlling the tension of driving wires connected to the upper-arm holder, and the shoulder rotational motion is assisted by the DC motor in the upper-arm holder in this robotic system. The mechanism for shoulder inner/outer rotation motion assist consists of a stator, a bearing holder, and a rotor. The rotor consists of a half cylinder, sliders, and a rack gear. The DC motor makes shoulder internal/external rotation motion by moving the rotor with respect to the stator. The DC motor and the mechanism for shoulder inner/outer rotation motion assist are installed in the arm holder. The details of the mechanism are shown in Fig. 2.



(a) Exoskeleton 1



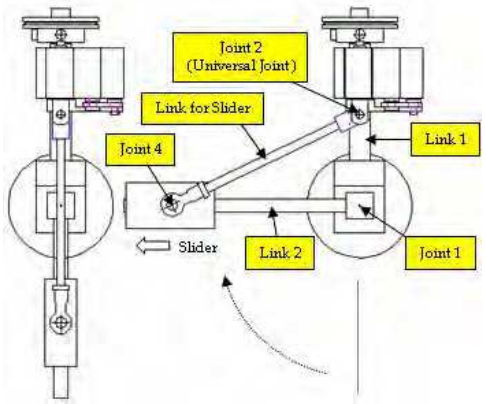
(b) Exoskeleton 2

Fig. 1 Examples of 4DOF upper-limb power-assist exoskeletons.

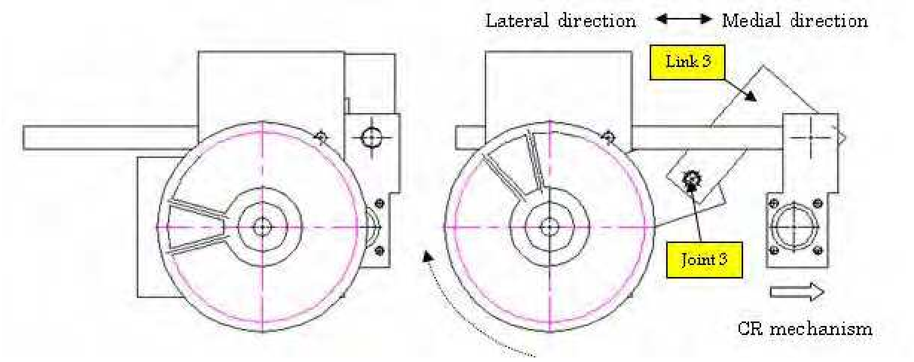
Fig. 2 Mechanism for shoulder inner/outer rotation motion assist.

The mechanism of the moving center of rotation of the shoulder joint (CR mechanism) used in the exoskeleton shown in Fig. 1 (a) is depicted in Fig. 3. The CR mechanism consists of a slider (made of ball-spline mechanism) and two links (link1 and link2, as shown in Fig. 3). The slider is installed between link1 and link2 of the exoskeleton and the upper-arm holder is installed on it.

The shoulder joint of the exoskeleton (i.e., joint between the link1 and the link2) is supposed to be located just behind the armpit of the user. This CR mechanism makes the CR of the exoskeleton shoulder joint move behind (farther position from the arm holder) in accordance with to the shoulder flexion angle in the case of flexion motion, and move inward (closer position of arm holder) in accordance with the shoulder abduction angle in the case of abduction motion. The link work mechanism is applied to realize this mechanism. In the case of shoulder flexion/extension motion, the link2 is vertically rotated with respect to the joint between the link1 and link2. As the link2 rotates vertically, the additional link (the link for the slider) is rotated with respect to joint2 (universal joint). The other end of the link for the slider is attached on the slider on the link2. Since the radius of the link2 and the link for the slider is different, the slider moves along the link2 according to the shoulder flexion angle.



(a) Shoulder Vertical Flexion Motion (Side View)



(b) Shoulder Horizontal Extension Motion (Top View)

Fig. 3 Motion of Centre of Rotation (CR) Mechanism.

In the case of shoulder abduction/adduction motion, the link1 is rotated about its axis according to the abduction/adduction angle. As the link1 rotates, joint3 is rotated with respect to the axis of the link1. The rotation of the joint3 causes the movement of the position of the joint2 along the lateral-medial direction as shown in Fig. 3 (b). As the position of the joint moves along the lateral-medial direction, the slider moves along the link2 since the link for the slider is connected to the joint2.

Usually, the movable range of human shoulder is 180° in flexion, 60° in extension, 180° in abduction, 75° in adduction, 100-110° in internal rotation, and 80-90° in external rotation. 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 minimally required motion in everyday life and the safety of the user, the shoulder motion of the 4DOF exoskeleton shown in Fig. 1 (a) is limited to 0° in extension and adduction, 90° in flexion, and 90° in abduction. The limitation of its forearm motion is decided to be 50° in pronation and 80° in supination, and that of elbow motion is decided to be 120° in flexion and 0° in extension. In the case of 4DOF exoskeleton shown in Fig. 1 (b), the elbow joint motion of the exoskeleton system is limited between 0° and 120°, and the limitation of the shoulder joint motion of the exoskeleton system are decided to be 0° in extension and adduction, 90° in flexion, 90° in abduction, 90° in internal rotation, and 50° in external rotation.

Those exoskeletons are controlled to assist the upper-limb motion of the user in accordance with the user's motion intention by monitoring the EMG signals of certain muscles involved in the upper-limb motion. In order to assist all upper-limb motion except the wrist dorso-palmar flexion and radio-ulnar deviation motion, at least 5DOF motion must be provided assuming that the location of the rotational center of the shoulder joint of the exoskeleton is the same as that of the user. As a matter of fact, more DOF is required to assist all upper-limb motion since human shoulder complex, which consists of the scapula, clavicle, and humerus and moves conjointly, itself provides 7 DOF for the upper-limb motion (Zatsiorsky, 1998). Therefore, some kind of adjustment mechanism is usually required to compensate for the ill-effect caused by the difference of the shoulder rotational center between the exoskeleton and the user (Kiguchi *et al.*, 2003a, 2003b, 2004, 2006a).

As far as the hardware of the exoskeletons is concerned, both mechanisms shown in Fig. 1 can be easily combined to make a 5DOF power assist exoskeleton that assists shoulder 3DOF motion (vertical and horizontal flexion/extension, and internal/external rotation motion), elbow flexion/extension motion, and forearm pronation/supination motion. As far as the controller (EMG-based controller) of the exoskeleton concerned, however, it is not easy to control the combined 5DOF motion based on the EMG signals because certain muscles are involved in several motions in the 5DOF. The details are discussed in the next section.

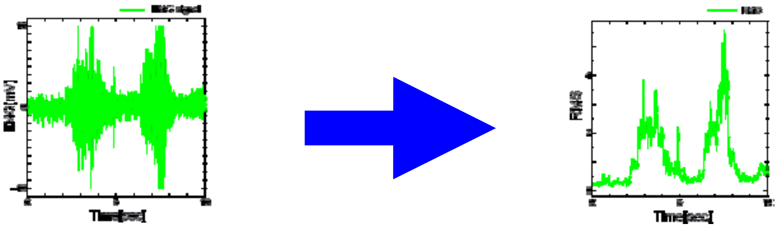
3. Electromyogram (EMG)

Electromyogram (EMG) signal (0.01-10mV, 10-2,000Hz) is one of the most important biological signals to understand human motion intention it is generated when the muscles contract. Features must be extracted from the raw EMG data since it is difficult to use the raw EMG data for input information of the controller. There are many kinds of feature extraction methods, e.g., Mean Absolute Value, Mean Absolute Value Slope, Zero

Crossings, Slope Sign Changes, Waveform Length, or Root Mean Square (Hudgins, 1993). Root Mean Square (RMS), one of the best feature extraction methods, is applied in this study because of its simplicity and effectiveness.

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N} v_i^2} \tag{1}$$

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 time is 500μsec in this study. Applying the RMS, the feature of the EMG signal can be effectively extracted in real-time as shown in Fig. 4.



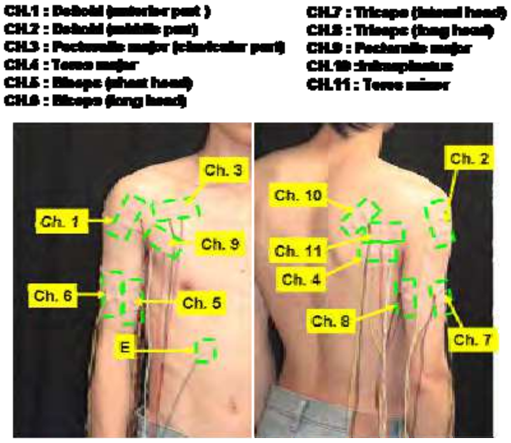
EMG Signal **RMS Signal**

Fig. 4. Feature extraction of EMG signal.

The magnitude of the RMS of the EMG signal is proportional to the activity level of the muscle. When the magnitude of the RMS of the EMG signals is not so large, the exoskeleton is controlled based on the wrist force sensor of the exoskeleton to avoid the misoperation (Kiguchi *et al.*, 2001-2002 & 2004-2007). When the user activates the muscles, the force sensor signals are ignored and the EMG-based control is applied. By applying sensor fusion with the EMG signals and the wrist force sensor signals, error motion caused by little EMG levels and the external force affecting to the user arm can be avoided.

Human elbow is mainly actuated by two antagonist muscles: biceps and triceps, although it consists of more muscles. The origin of the long head of biceps is connected to supraglenoid tubercle of the scapula, and that of the short head of biceps is connected to coracoid process of the scapula. The other side of biceps is connected to tuberosity of the radius and the bicipital aponeurosis. In the case of triceps, the origin of the long head is connected to infraglenoid tubercle of the scapula, that of the lateral head is connected to posterior surface and lateral border of the humerus and the lateral intermuscular septum, and that of the medial head is connected to posterior surface and medial border of the humerus and the medial intermuscular septum. The other side of triceps is connected to posterior part of the olecranon process of the ulna and the deep fascia of the dorsal forearm. Consequently, biceps and a part triceps are bi-articular muscles. For example, biceps is used to generate elbow flexion motion, shoulder vertical flexion motion, and also forearm supination motion especially when the elbow joint is in the flexed position. Therefore, when those motions are generated simultaneously, the EMG-based control of power-assist exoskeleton is not very easy to be realized.

(a) Electrodes for the exoskeleton 1



(b) Electrodes for the exoskeleton 2

Fig. 5 Location of each electrode.

In order to assist the 4DOF motion (shoulder vertical flexion/extension, shoulder horizontal flexion/extension, elbow flexion/extension, and forearm supination/pronation) of the exoskeleton1 shown in Fig. 1 (a), the EMG signals measured at 12 points (Deltoid – anterior part, Deltoid – posterior part, Pectoralis Major – clavicular part, Teres Major, Biceps – short head, Bicesp – long head, Triceps – long head, Triceps – lateral head, Pronator Teres, Flexor Carpi Radialis, Anconeus, and Supinator) of the related muscles are measured with the electrodes (NE-101A: Nihon Koden Co.) through the amplifier (MEG-6108: Nihon Koden Co.) and analyzed in the controller of the exoskeleton. The location of each electrode is depicted in Fig. 5 (a).

In order to assist the 4DOF motion (shoulder vertical flexion/extension, shoulder horizontal flexion/extension, shoulder internal/external rotation, and elbow flexion/extension) of the exoskeleton2 shown in Fig. 1 (b), the EMG signals measured at 11 points (Deltoid – anterior part, Deltoid – medial part, Pectoralis major - clavicular part, Teres major, Biceps – short head, Bicesp – long head, Triceps – long head, Triceps – lateral head, Pectoralis major, Infraspinatus, and Teres minor) of the related muscles are measured with the electrodes through the amplifier and analyzed in the controller of the exoskeleton. The location of each electrode is depicted in Fig. 5 (b).

4. Control of Upper-Limb Exoskeletons

In order to control the upper-limb exoskeleton in accordance with the user's motion intention, EMG-based control is mainly applied. In order to cope with the problems of the EMG-based control caused from human anatomy, multiple neuro-fuzzy controllers are applied. When the magnitude of the muscle activity levels of the user is little, however, the exoskeleton is controlled based on the wrist force sensor to avoid the misoperation (Kiguchi *et al.*, 2001-2002 & 2004-2007). When the user activates the muscles, the force sensor signals are ignored and the EMG-based control is applied. The basic architecture of the whole control system for the exoskeletons shown in Fig. 1 (a) is shown in Fig. 6. The controller basically consists of three stages (first stage: input signal selection stage, second stage: posture region selection stage, and third stage: neuro-fuzzy control stage). In the first stage of the controller, the EMG based control or the wrist sensor based control is applied in accordance with the muscle activity levels of the user. In the second stage of the controller, a proper neuro-fuzzy controller is selected according to the shoulder and the elbow angle region. In the third stage of the controller, the desired torque command for each joint is calculated with the selected neuro-fuzzy controllers to realize the effective motion assist for the user.

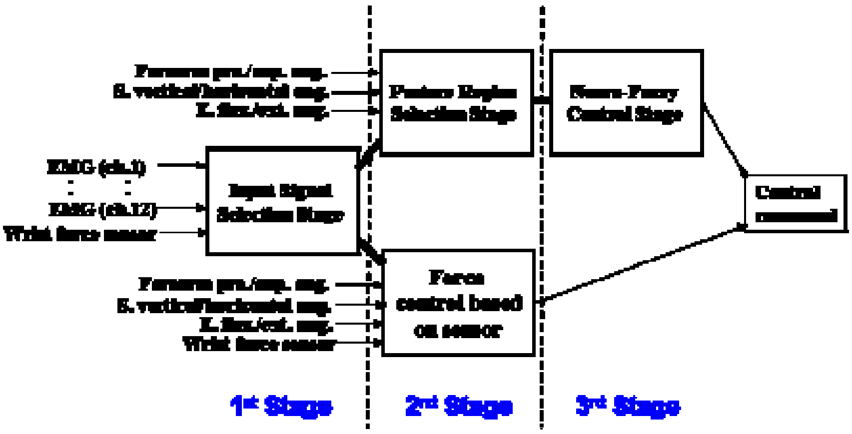


Fig. 6 Architecture of controller.

In the first stage of the controller, proper input information for the controller is selected according to the user's muscle activity levels. The EMG-based control or the wrist sensor based control is selected in this stage in accordance with the muscle activity levels of the user. If the activity level of every muscle is little, the wrist sensor based control is selected in this stage. When the user activates the muscles, the EMG-based control is selected. These control methods are gradually switched according to the situation by applying the fuzzy switching. The membership function (PB: Positive Big) of each muscle is used to switch the controller input information.

The EMG-based control rules are sometimes different when the arm posture is changed since role of each muscle is changed according to the arm posture because of anatomical reason. In order to cope with this problem, multiple neuro-fuzzy controllers are designed and applied under certain arm posture region in the second stage (Kiguchi, 2002, 2003a, 2004). A properly designed neuro-fuzzy controller is prepared for each elbow and shoulder angle region. Based on the joint angle, the movable range of elbow angle, shoulder vertical angle, and shoulder horizontal angle regions is divided into three regions (FA: flexed angle, IA: intermediate angle, and EA: extended angle), respectively. By applying the membership functions, the appropriate controllers are moderately selected in accordance with the upper-limb posture of the user.

In the third stage, selected neuro-fuzzy controllers generate the required torque command for each joint. The architecture of the neuro-fuzzy controller for the exoskeleton shown in Fig. 1 (a) is depicted in Fig. 7. Here, Σ means the summation of the inputs and Π means the multiplication of the inputs. Two kinds of nonlinear functions (f_G and f_S) are applied to express the membership function of the neuro-fuzzy controller.

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

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

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

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

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

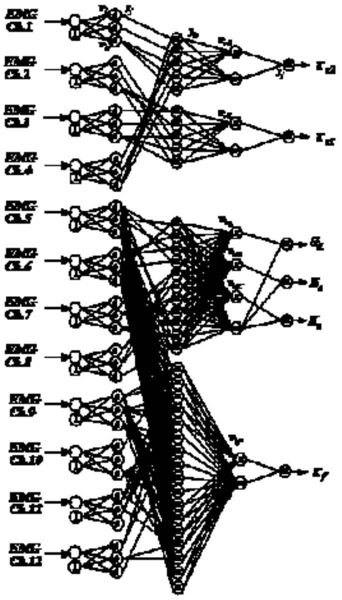


Fig. 7 Neuro-fuzzy controller.

The structure of the neuro-fuzzy controller is basically the same as the conventional simplified fuzzy controller since it can be easily designed based on our anatomical knowledge and the results of previously performed experiment. The neuro-fuzzy controller consists of five layers (input layer, fuzzifier layer, rule layer, defuzzifier layer, and output layer). In the fuzzifier layer, the degree of fitness of each input signal (each RMS) for each fuzzy set (ZO: ZERO, PS: Positive Small, and PB: Positive Big) is calculated. In the rule layer, the degree of fitness of each rule is calculated. The output from the neuro-fuzzy controller (i.e., the desired torque for shoulder and forearm motion, and the desired impedance and angle change of elbow motion) is calculated in the defuzzifier layer.

The amount of weights of consequence part of the control rules, which are concerned with elbow flexion motion, in the neuro-fuzzy controllers are defined as functions of the activity levels of the related muscles used for the shoulder vertical motion and forearm supination motion. So that the activity levels of the related muscles used for the other motion modify the related control rules effectively (Kiguchi, 2007).

When the user of the exoskeleton is changed, the controller is adjusted for the user's condition using the error back-propagation learning algorithm (Rumelhart, 1986). The evaluation function is written as:

$$E = \frac{1}{2}((\theta_d - \theta)^2 + \alpha \sum (RMS_d - RMS)^2) \tag{6}$$

where θ_d is the desired joint angle indicated by the user using the motion indicator, θ is the measured shoulder and elbow angle, α is a coefficient which changes the degree of consideration of the muscle activity minimization, RMS_d is the desired muscle activity level of certain muscle, and RMS is the measured muscle activity level of certain muscle. The desired joint angles are indicated by the user's hand motion (the other side of the assisted upper-limb) using the motion indicator shown in Fig. 8. The weights in all of antecedent part and some of consequence part of neuro-fuzzy controllers are modified to minimize the amount of the evaluation function. After the controller adjustment, appropriate power-assist can be carried out with the desired assist level.

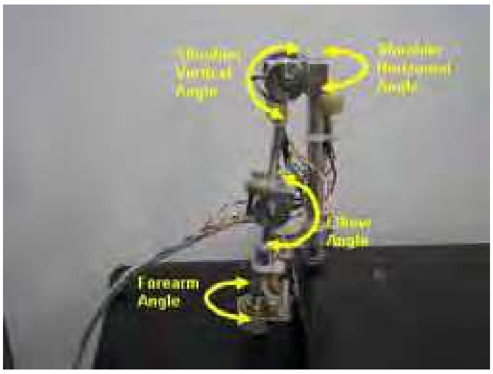
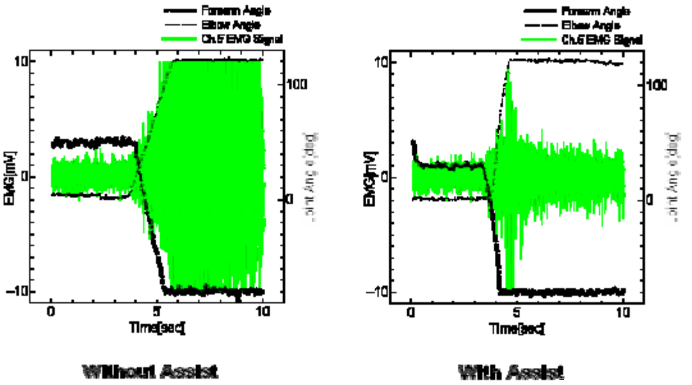


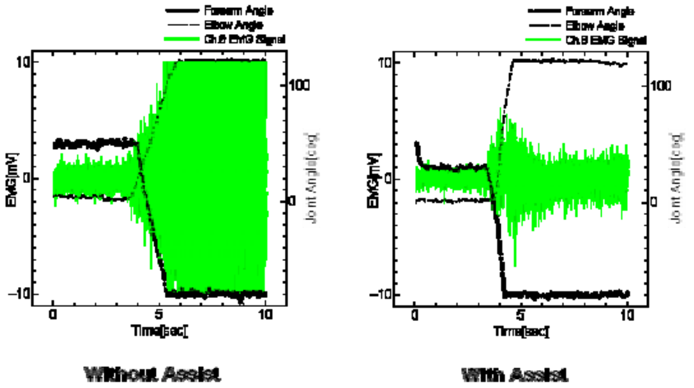
Fig. 8 Motion indicator.

5. Upper-Limb Motion Assist

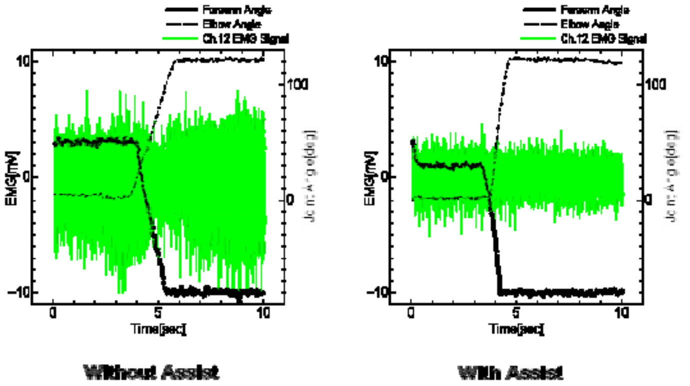
Upper-limb motion assist experiment has been carried out with and without assist of the 4DOF active exoskeleton1 (Fig. 1 (a)) to evaluate its effectiveness. Two kinds of motion are carried out by healthy young male subjects in the experiment. If the motion is properly assisted by the proposed exoskeleton, the magnitude of the muscle activity level is supposed to be reduced for the same motion when the motion is assisted by the exoskeleton.



(a) Biceps (short head) – ch.5



(b) Biceps (long head) – ch.6



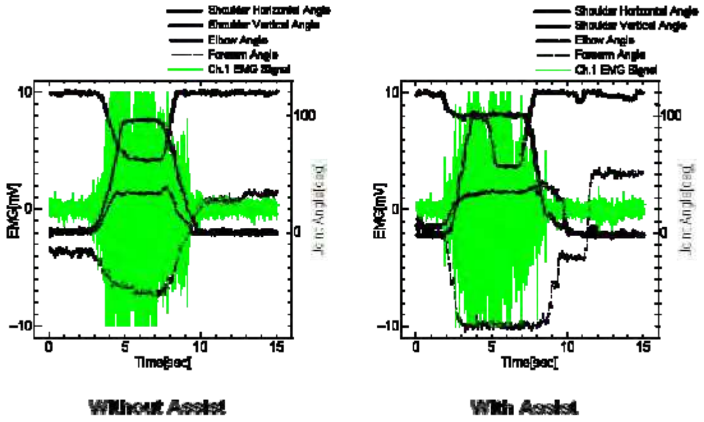
(c) Supinator – ch.12

Fig. 9. Experimental results of motion 1.

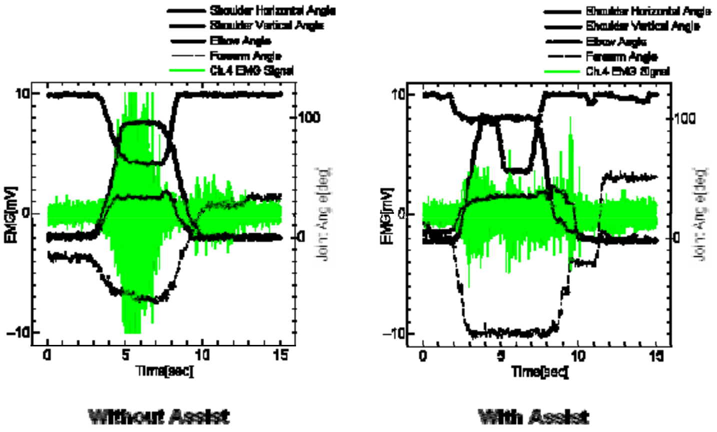
For the first motion (motion 1) in the experiment, cooperative motion of elbow flexion motion and forearm supination motion is performed with and without assist of the exoskeleton1. The results are shown in Fig. 9. Here, only the results of biceps (ch.5 & ch.6) and supinator (ch.12) are shown as representative results, since these are the most active muscles for this motion.

One can see that the activity level of each muscle is reduced for the same motion when the motion is assisted by the exoskeleton.

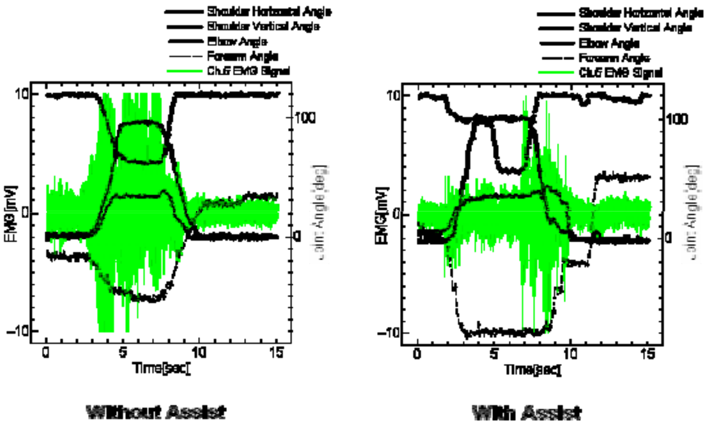
For the second motion (motion 2) in the experiment, cooperative motion of shoulder vertical motion, shoulder horizontal motion, elbow motion, and forearm motion is performed with and without assist of the exoskeleton1. The results are shown in Fig. 10. Here, only the results of deltoid anterior part (ch.1), teres major (ch.4), biceps short head (ch.5), triceps long head (ch.7) and pronator teres (ch.9) are shown as representative results.



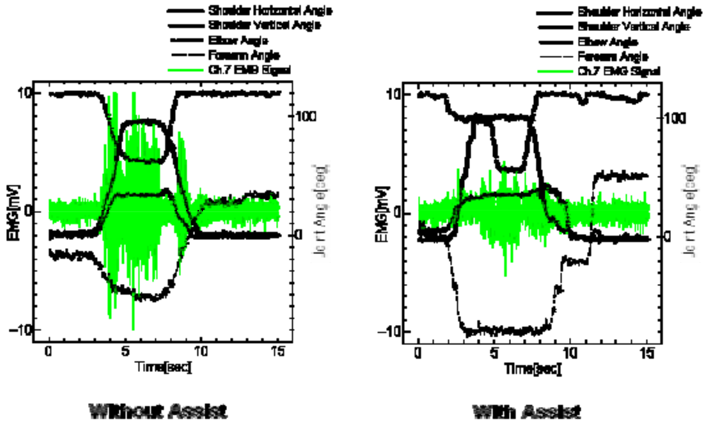
(a) Deltoid (anterior part) - ch.1



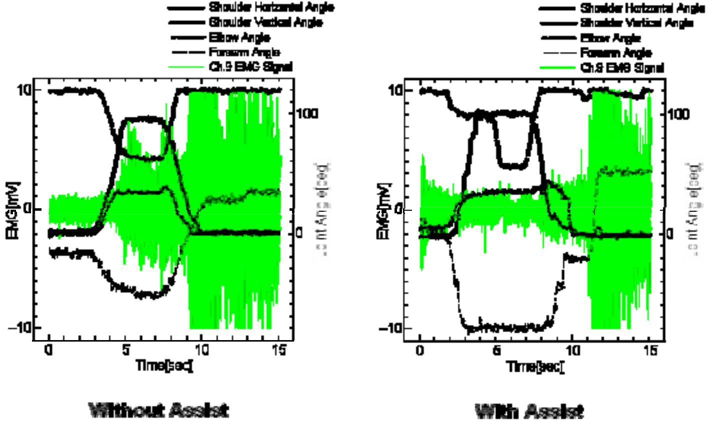
(b) Teres major - ch.4



(c) Biceps (short head) - ch.5

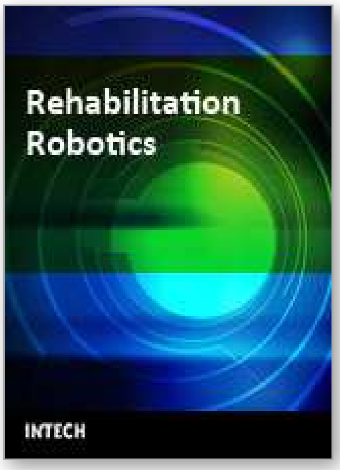


(d) Triceps (long head) - ch.7



(e) Pronator teres - ch.9

Fig. 10. Experimental results of motion 2.



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