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Neuro-Fuzzy based Motion Control of a Robotic Exoskeleton: Considering End-effector Force Vectors

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Abstract **- To assist physically disabled, injured, and/or elderly persons, we have been developing a 3DOF exoskeleton robot for assisting upper-limb motion, since upper-limb motion is involved in a lot of activities of everyday life. The exoskeleton robot is mainly is controlled by the skin surface electromyogram (EMG) signals, since EMG signals of muscles directly reflect how the user intends to move. This paper introduces the mechanism of the exoskeleton robot and also proposes a control method of the exoskeleton robot considering the generated end-effector force vectors.**

Index Terms - Wearable robot, power assist, biorobotics, electromyogram, neuro-fuzzy control.

I. INTRODUCTION

The numbers of people of aged society are increasing at an alarming rate especially in some countries. In addition to geriatric disorders, physical disabilities such as full or partial loss of function in shoulder, elbow or wrist is appears due to disease processes including trauma, sports injuries, occupational injuries, spinal cord injuries, and strokes. To assist physically weak persons such as elderly, injured, and/or disabled persons who have lost their original body functioning of motion, extensive research has been carried out [1]-[6] in many branch of welfare robotics to compensate for their lost functions for providing an independent life and play a more productive role in society. Exoskeleton robot is one of the expected products of new assistive technology of welfare robotics.

Since human upper-limb motion is used in a lot of activities of everyday life, we have been developing exoskeleton robot for rehabilitation and/or daily motion assist for upper-limb [2]-[4] of the elderly or physically weak persons so that they can perform their daily tasks easily.

Skin surface electromyogram (EMG) signals directly reflect how the user intends to move. So, one of the leading ideas of the exoskeleton research is to directly use human physiological signal to control the exoskeleton robots. Therefore, exoskeleton robot is able to assist the motion of the user effectively by applying the user's EMG signals as input signals to the robot controller.

In this paper, we introduce the modified mechanism of mobile exoskeleton robot and propose a control method for a 3DOF (shoulder vertical and horizontal flexion/extension, and elbow flexion/extension) exoskeleton robot considering the generated end-effector force vectors, for rehabilitation and daily motion assist for physically weaken persons. Considering many physically weak persons use a wheel chair, the exoskeleton robot is installed on the mobile wheel chair. The exoskeleton robot is activated based on the EMG signals and the generated wrist force (i.e., the force generated between the exoskeleton robot wrist and robot user's wrist) during the upper limb motion of the user. The controller responsible for desired motion of the exoskeleton robot is comprised of *force sensor based controller* (FBC) and *EMG based controller* (EBC) coupled with *obstacle avoidance controller* (OAC). The EMG signals from shoulder and elbow muscles and generated wrists forces are used as input parameters to build a part of total architecture of the controller. Control is carried out based on the EMG signals (i.e.; by the EBC), when exoskeleton robot user's upper-limb muscles activity level is high. However when the muscle activity level of robot users is low, control is carried out based on the wrist force sensor signals (i.e.; by the FBC). In the intermediate activity level of muscles both the EBC and the FBC acts simultaneously [2]. In addition to provide active assist mode of rehabilitation the controller is responsible to assist the upper-limb motions to perform daily activity.

Neuro-fuzzy control, which is a combination of flexible fuzzy control and adaptive neural network control, has been applied to realize the real time control of the exoskeleton robot [2]-[4]. In the existing research, the EBC generates the desired torque for each joint based on the EMG signals of the related muscles. However, it is important to take into account the hand trajectory (i.e.; the tip trajectory of the exoskeleton) for the practical application. It is known that the hand trajectories of point-to-point movements are generally straight [7]. In this paper, we take into account the hand trajectory of the user in addition to the EMG signals of the user to realize the better and more stable motion assist.

In next section of this paper, an overview of the development of exoskeleton robot is presented. Features of the EMG signals are described in section III. Details about the proposed controller have been explained in section IV. In section V, effectiveness of the proposed controller has been evaluated and finally the paper ends with the conclusion in section VI.

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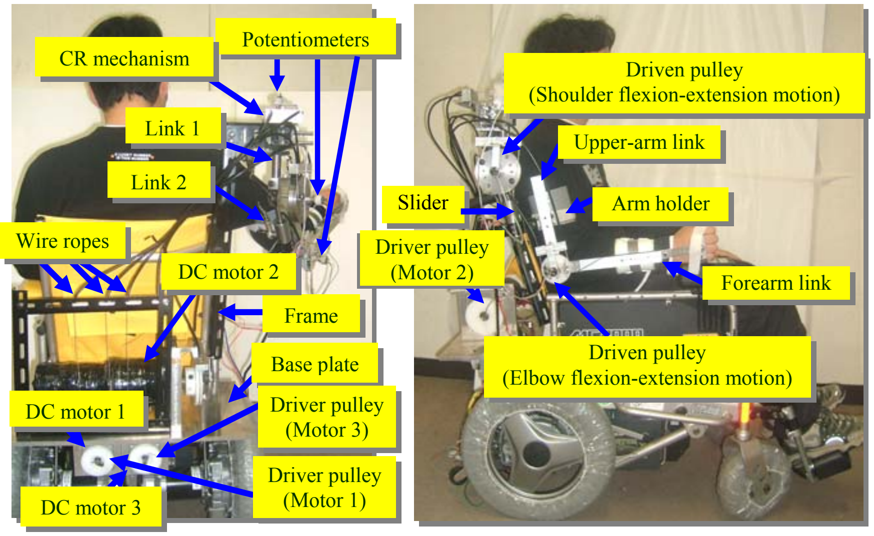


(a) Rear View (b) Side View

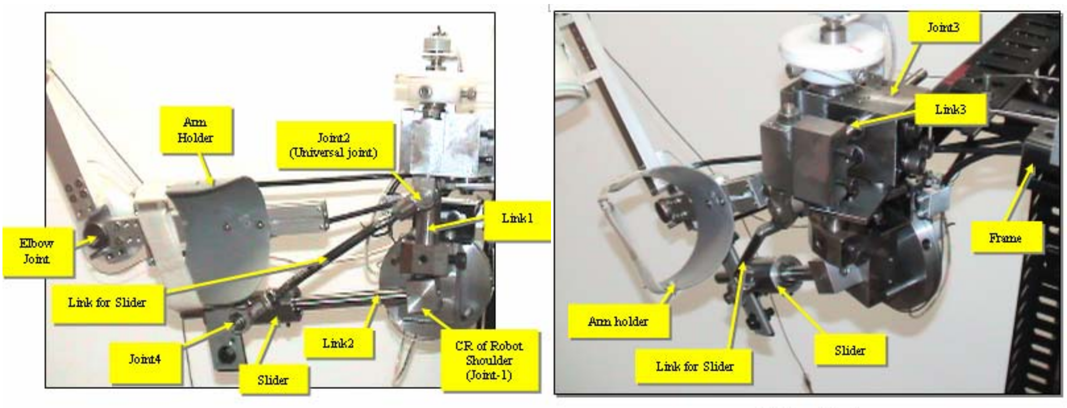
Fig. 1 Mobile Exoskeleton Robot

II. ROBOTIC EXOSKELETON

The exoskeleton robot system as shown in Fig.1 is developed considering the design criteria (e.g., light weight of exoskeleton to provide low mass moment of inertia, safety in operation, comfort of wearing, easiness in maintenance) for rehabilitation and/or daily motion assist for upper limb motion (shoulder vertical and horizontal flexion/extension, and elbow flexion/extension) of physically weaken persons, and then attached to a mobile wheel chair. It mainly consists of a shoulder motion support part, an elbow motion support part, a wrist force sensor, and a mobile wheel chair. The mobile wheel chair itself has 2DOF which provides an independent movement of physically weaken persons. The shoulder motion support part consists of an upper arm link, driver and driven pulleys (one for shoulder horizontal flexion/extension motion, another one for shoulder vertical flexion/extension motion), DC motors, potentiometers, an arm holder, and the mechanism of moving centre of rotation (CR) of shoulder joint. The DC motor1 for shoulder horizontal flexion/extension motion is installed at the rear bottom side of the wheel chair (i.e., just above the driving motors for rear wheels of the wheel chairs) and the DC motor2 for shoulder vertical flexion/extension motion is installed acorssly above the DC motor1 (Fig. 1 (a)).

In order to generate 2DOF shoulder motion (shoulder vertical and horizontal flexion/extension motion), motor pulleys (Fig.1 (a)) act as driver pulleys and pulleys connected to the shoulder joint, as shown in Fig.1 act as driven pulleys. Power is transmitted from driver to driven pulley via stainless steel wire ropes, almost like a chain and sprocket mechanism.

The upper arm link which is fixed with slider (Fig. 1 (b)) carries the arm holder as well as the elbow motion support part also. Arm holder made of thin flexible plastic with magic tape ribbon (as shown in Fig. 1 (b)) holds user's upper arm. The manipulation of robot user's upper arm is carried out by controlling the arm holder motion. The distance between the arm holder and the CR of the shoulder joint of the exoskeleton robot is moderately adjusted in accordance with the shoulder motion, in order to cancel out the ill effects caused by the position difference of the CR between the system's shoulder and the human shoulder [3]. The CR mechanism (Fig. 2) of the robotic exoskeleton consists of a slider (made of ball-spline mechanism) and two links (link1 and link2, as shown in Fig. 2). The slider is installed between link1 and link2 of the



(a) Side view (b) Rear side view

Fig. 2 Centre of Rotation mechanism

exoskeleton. This CR mechanism is a modified version of that of the existing exoskeleton [3]. The motion of this CR mechanism is depicted in Fig. 3.

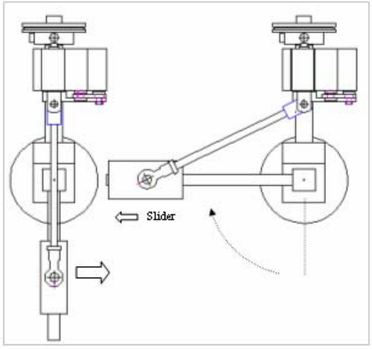
The exoskeleton shoulder joint (i.e., joint between the link1 and the link2) is supposed to be located just behind the armpit of the user. This CR mechanism makes the CR of the exoskeleton shoulder joint move behind (farther position from the arm holder) in accordance with to the shoulder flexion angle 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 has been 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) (Fig. 2). 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 (Fig. 3 (a)).

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.

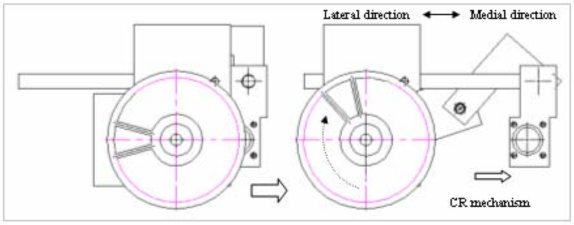
In this exoskeleton robot, the maximum moving distances of the arm holder from shoulder-joint-center of robot are 67 mm (i.e., forward movement) for the flexion/extension motion and 84 mm (i.e., inward movement) for the abduction/adduction motion. Compare to the existing research [3], forward moving is improved by 15.52% for shoulder vertical flexion/extension motion and inward moving is improved by 23.52% for shoulder horizontal flexion/extension motion.

1DOF elbow motion assist part of the exoskeleton robot (Fig. 1) consists of a forearm link, pulleys, a DC motor, a potentiometer, a wrist-griper and a force sensor. The DC motor3 is installed parallely with motor1 at the rear bottom side of the wheel chair (Fig. 1 (a)). For generating elbow flexion/extension motion, motor pulley (Fig. 1 (a)) acts as in Fig. 1 (b)) acts as driven pulley. Same as shoulder motion support part; from driver to driven pulley power is transmitted via stainless steel wire ropes.

To hold robot user's wrist in proper position an adjustable soft wrist-griper, as shown in Fig. 4, is set-up on the forearm link via two beams. A three axis Pico force sensor [PD3-30-10-015, Nitta], which is installed in between forearm link and wrist-griper (as shown in Fig. 4), is used to measure the generated wrist force (i.e., the force caused from the motion difference between the exoskeleton robot and the human subject's wrist). Maximum allowable load to the force sensor is 15 N.cm in X and Y axes and 15 N in Z axes.



(a) Shoulder Vertical Flexion Motion (Side View)



(b) Movement of CR mechanism, Shoulder Horizontal Extension Motion (Top View)

Fig. 3 Motion of Centre of Rotation (CR)

Potentiometers [6187 R1K L1.0] are attached concentrically (Fig. 1 (b)) with the driven pulleys to measure the angle of rotation of exoskeleton robot joints.

Considering many physically weak persons use a wheel chair, the exoskeleton robot as explained above is installed to the auto-wheel chair [MC2000, Suzuki, Japan] (Fig. 1) and assists the horizontal flexion/extension and vertical flexion/extension motion of the shoulder joint and flexion/extension motion of the elbow joint of subjects.

Usually, the movable range of human elbow is between -5º and 145º and that of human shoulder is 180º in flexion, 60º in extension, 180º in abduction and 75º in adduction.

Considering the practical applications to everyday life and the safety, the elbow motion is limited between 0º to 120º and that of shoulder motion is limited to 0º in extension and adduction, 90º in flexion, and 90º in abduction, in the proposed exoskeleton robot system. Note that, maximum movable range of the proposed exoskeleton robot as stated earlier is kept by both hardware and software.

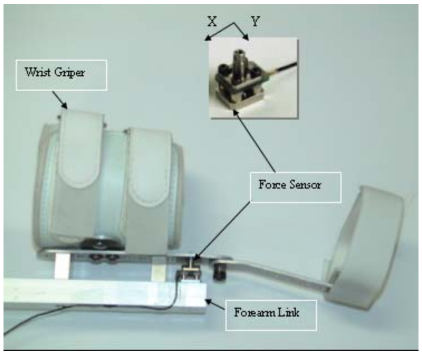


Fig. 4 Wrist griper and location of force sensor

III. EMG SIGNAL PROCESSING AND MUSCLES MODEL

The central nervous system (CNS) drives and controls the skeletal muscles by sending the motor command to each muscle via motor neurons, which in turn is responsible for posture maintenance and voluntary movement. These signals activate the muscle contractions and tensions, which results in joint torques. Since we cannot directly measure the motor neuron activity and since the EMG activity is a reasonable reflection of a firing rate of a motor neuron, in our study we measured surface EMG signals as a record of the motor commands to the muscles.

Usually EMG signals consist of wide range of frequency, so that it is difficult to reduce noise by filtering. Furthermore, it is difficult to directly use raw EMG data as input information to the controller. Therefore, features have to be extracted from the noisy raw EMG data. The RMS value is calculated to extract the feature of the raw EMG signals in this study. The RMS value is a measure of power of the signal and is widely used in most applications. The equation of RMS value is written as:

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

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.

Disk type surface EEG electrodes (10mm Ag/AgCl NE-121J, Nihon Kohden) were attached to the user's skin surface by adhesive tapes at locations recommended in [8] to measure the EMG signals of shoulder and elbow muscles. In our study, eight kinds of EMG signals from shoulder muscles (e.g., deltoid anterior part, pectoralis major, teres major and deltoid posterior part) and elbow muscles (e.g., biceps and triceps) (Fig. 5) of the users are monitored and used as input information to control the exoskeleton robot system.

Note that, prior to send raw EMG and force sensor signals to A/D, they are amplified and then sampled at a rate 2 kHz.

Ch.1: Deltoid (anterior part)
Ch.2: Deltoid (posterior part)
Ch.3: Pectoralis major (clavicular part)
Ch.4: Teres major
Ch.5: Biceps (proximal part)
Ch.6: Biceps (lateral part)
Ch.7: Triceps (lateral part)
Ch.8: Triceps (medial part)

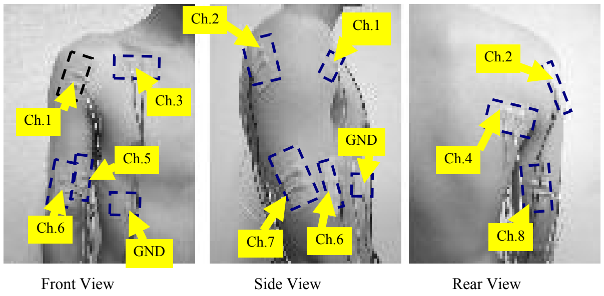


Fig. 5 Location of electrodes

IV. EXOSKELETON ROBOT CONTROLLER

The *force sensor based controller* (FBC) and the *EMG based controller* (EBC) are prepared for control, and integrated and coupled with *obstacle avoidance controller* (OAC) to form a total automatic controller. Figure 6 shows the schematic diagram of the controller. Selection of the controller for desired motion of assist is depends on input signals and usually obeys the following principles.

Proper controller is selected based on the user's muscles activation level [4]. Control is carried out based on the EMG signals (i.e., by the EBC), when user's upper-limb muscles activity level is high (i.e., when the EMG levels of the user is high). However when the muscle activity level of robot users is low (i.e., when the EMG levels of the user is low), control is carried out based on the wrist force sensor signals (i.e., by the FBC). In the intermediate activity level of muscles, both the EBC and the FBC act simultaneously.

A. *Force Sensor Based Controller (FBC)*

In FBC, force control is carried out to make the generated wrist forces become zero. The outputs of the controller are the joint torque commands for shoulder and elbow joint of the robotic exoskeleton system.

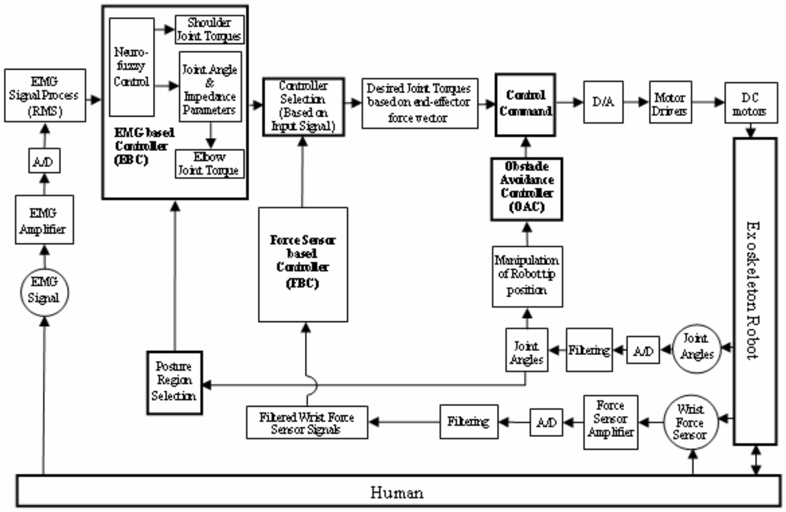


Fig. 6 Schematic diagram of the controller

B. EMG Based Controller (EBC)

In the EBC, multiple neuro-fuzzy controllers have been designed and applied under certain arm posture region [2]. Based on the movable range of elbow joint is divided into three regions and that of shoulder joint is divided into nine regions. More details about the controllers are explained in [2].

Each neuro-fuzzy controller contains 21 rules (ten rules for shoulders and eleven rules for elbow). Even though there exists difference in anatomy and the way of muscles use between persons, the neuro fuzzy controllers are able to adapt themselves to any user by adjusting all of the antecedent part and some of the consequent part of the controllers by using the back propagation learning algorithm [2].

Three kinds of fuzzy linguistic variables (ZO: zero; PS: positive small; PB: positive big) are prepared for each RMS of EMG. The architecture of the neuro-fuzzy controller is shown in Fig.7. Here Σ means summation of inputs and Π means multiplication of inputs. Two kinds of nonlinear functions (f_G: Gaussian function and f_S: Sigmoidal function) are prepared to express the membership function of the antecedent part of the neuro-fuzzy controller. For generating the shoulder motion, the output of the neuro-fuzzy controller is the torque command and that of for generating the elbow motion are the desired joint angle and impedance of the exoskeleton elbow joint [2].

Output of the EBC is thereafter used to derive the instantaneous force vectors at the robot end-effector (*IFV*) in order to take into account the generated end-effector force vectors, since smooth trajectory of the end-effector must be generated [7]. The equation of derived *IFV* is written as:

$$F_I = J^{-T}\tau_p \tag{2}$$

where, F_I is the instantaneous force vectors at the robot end-effector, τ_p is the projected torque command generated from the EBC, and J is a Jacobian matrix.

Average force vectors (*AFV*) of the previous *IFV* derived from the EBC is then calculated at every sampling. The *IFV* is then compared with the *AFV* and a mean of these two is calculated to generate the desired joint torques of the robotic exoskeleton. The equation of *AFV*, command force vectors and desired joint torques are listed below:

$$AFV = \frac{1}{N_{AFV}}\sum_{i=1}^{N} F_i \tag{3}$$

$$F_c = (F_I + AFV)/2 \tag{4}$$

$$\tau_d = J^T F_C \tag{5}$$

where, F_i is the *IFV* at the i^{th} sampling, N_{AFV} is the number of sample in a segment to calculate *AFV*, F_C is the command force vectors and τ_d is the desired joint torques. The number of sample is set to be 2000 in this study. The torque command for the exoskeleton robot joint is then transferred to the torque command to the driving motors.

Since our exoskeleton robot is installed on a mobile wheel chair, the EBC and the FBC should be coupled with the OAC to avoid unexpected collision with the frame of wheel chair. In order to achieve this, virtual repulsive force field is created by the combination of virtual spring and damper, on the frame surface of the mobile wheel chair so that when robotic exoskeleton reach near to the frame surface, it is push back by the virtual repulsive forces and thus allow the exoskeleton to avoid collision with the frame of the mobile wheel chair.

A two layer virtual wall (as a virtual obstacle) is created to cover the frame of wheel chair (Fig. 8). Between *virtual wall surface 1* and *2*, relatively soft spring and damper is chosen compare to those in between *virtual wall surface 2* and obstacle (i.e., the frame of the mobile wheel chair) to exert a relatively low repulsive forces when exoskeleton knocks the *virtual wall surface 1*. However, exoskeleton robot tip subjects to strong repulsive forces when it knocks to *virtual wall surface 2*.

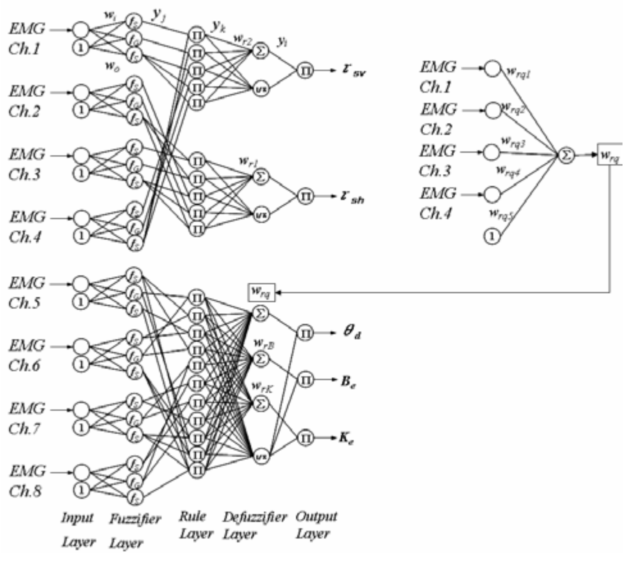


Fig. 7 Neuro-fuzzy controller

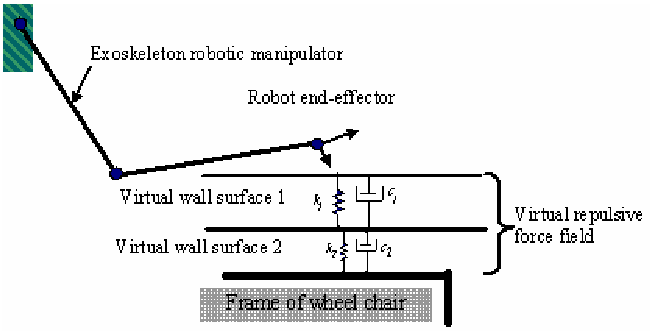


Fig. 8. Structure of robotic exoskeleton and virtual obstacle

V. EXPERIMENT

Experiment has been performed with healthy male human subjects to evaluate the effectiveness of the proposed control method to assist the upper limb motion. The experimental set-

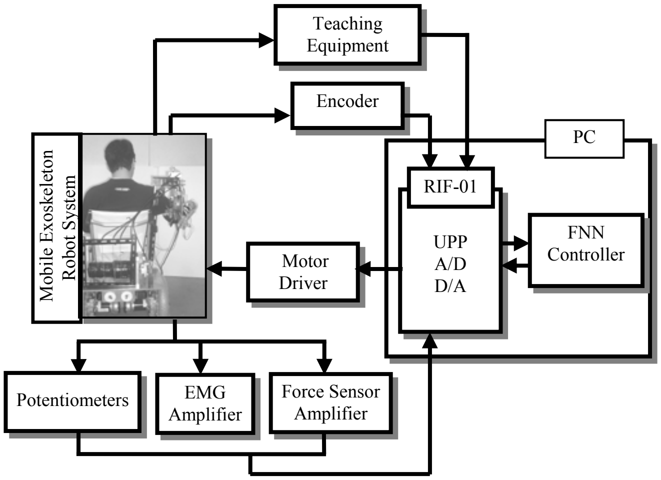
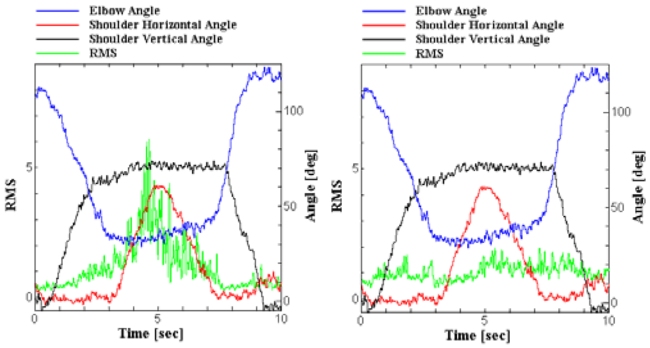


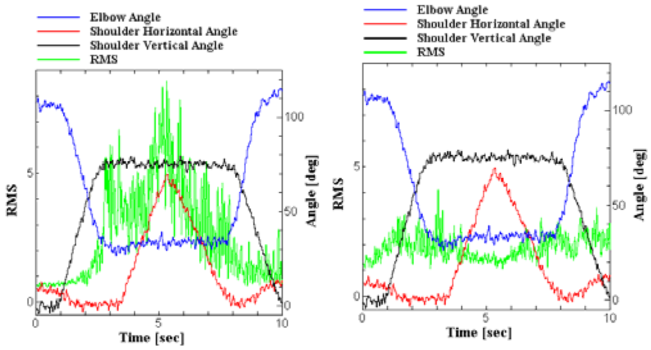
Fig. 9 Experimental set-up

up is shown in Fig. 9. In this experiment, upper limb motion (a co-operative motion of elbow and shoulder joint for gripping a object and to put it to the desired place and finally back to the initial position of arm posture) is performed by the proposed controller (i.e., FBC and EBC coupled with OAC) with and without assist of exoskeleton robot. Figure 10 shows the experimental results with assist of the exoskeleton robot system (where N_{AFV} is set to 2000). A similar motion (as of with assist of robot) was performed without assist of exoskeleton robot system for comparison, and the results are depicted in Fig. 11.



(a) Deltoid (posterior part) (b) Biceps (proximal part)

Fig. 10 Experimental result with assist of robotic exoskeleton



(a) Deltoid (posterior part) (b) Biceps (proximal part)

Fig. 11 Experimental result without assist of robotic exoskeleton

Here, only the results on ch.2 (posterior part of deltoid), and ch.5 (proximal part of biceps) are shown since they are the most active muscles among the shoulder and elbow muscles, respectively. Comparing Fig. 10 with Fig. 11, it reveals that trajectory generated with assist of exoskeleton robot (Fig. 10) and without assist of exoskeleton robot (Fig. 11) is almost the same one with no up and down from the start point to the end point of the trajectory which ensures that the generated motion is the smoother one by the proposed control method. Moreover, it also conclude that muscles activities are much lower when subject motion is assisted by the proposed exoskeleton robot with the proposed control method.

VI. CONCLUSION

The mechanism of the proposed mobile exoskeleton robot was introduced for rehabilitation and daily upper-limb motion assist of physically weaken persons. The effectiveness of the controller (i.e., *force sensor based controller* and *EMG based controller* coupled to *obstacle avoidance controller*) was proposed considering *IFV* for smooth motion assist. The experimental results showed the effectiveness of the proposed method.

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