Robotic Exoskeleton for Rehabilitation and Motion Assist

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Abstract **– For elderly and or physically disabled people who have lost their body functioning of motions due to geriatric disorders, and/or disease processes including trauma, sports injuries, spinal cord injuries, occupational injuries, and strokes, we have been developing a 3DOF mobile robotic exoskeleton for rehabilitation and for assisting motion of elbow and shoulder, since human shoulder and elbow motions are involved in a lot of activities of everyday life. The robotic exoskeleton is mainly activated and is controlled by the skin surface electromyogram (EMG) signals, since EMG signals of muscles directly reflect how the user intends to move. This paper focused on the mechanism of mobile robotic exoskeleton and proposed passive and active assist mode of rehabilitation scheme in addition to assist daily upper-limb motion by the aid of robotic exoskeleton. The proportional derivative (PD) control has been applied to the controller for the passive mode of rehabilitation whereas neuro-fuzzy based biological controller is responsible for active assist mode of rehabilitation as well as to assist daily upper limb motion**.

Index Terms - Robotic exoskeleton, rehabilitation, biological control, electromyogram, neuro-fuzzy control.

I. INTRODUCTION

Physical disabilities such as full or partial loss of function in shoulder, elbow or wrist is a common complaint due to geriatric disorder and other disease processes including trauma, sports injuries, spinal cord injuries, occupational injuries, and strokes.

Rehabilitation program is the main mode of treatments for this kind of disabled patients who are suffering by the above mentioned diseases and others. Usually, treatment for those conditions relies to some extent on manipulative physiotherapy procedures which are sometimes extremely labor intensive and requires high levels of patient to patient caring from high skill physiotherapists or medical personnel. Since the number of cases is huge and the duration of treatment is long, extensive research has been carried out in many branch of welfare robotics [1]-[4], [11] for elderly, and/or disabled persons who have lost their original body functioning, to compensate for their lost functions and thus providing an independent life and play a more productive role in society. *Robotic exoskeleton* -a new assistive technology of welfare robotics now-a-days holds its position besides elderly or physically disabled peoples to assist in this program.

Since human upper-limb motion is used in a lot of activities of everyday life, we have been developing robotic exoskeleton for rehabilitation and/or daily motion assist for upper-limb [5], [7] of the elderly or physically weak persons so that they can perform their daily tasks easily.

In this paper, we focused on the mechanism of mobile exoskeleton robot and proposed passive and active assist mode of rehabilitation scheme in addition to assist daily upper-limb motion by the aid of robotic exoskeleton. The robotic exoskeleton is supposed to be directly attached to a subject's (robot user's) upper limb and is controlled 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 and assists the horizontal and vertical flexion-extension motion of the shoulder joint and flexion-extension motion of the elbow joint of the subject.

In passive mode of rehabilitation, users/ subjects operate a 3DOF upper limb prototype motions indicator by his/her hand to control the motion of the robotic exoskeleton systems. The reliable PD control has been applied for this controller. Joint kinematics of the robotic exoskeleton are fed to the controller to control the exoskeleton robot and thus providing passive mode of rehabilitation as well as assists the upper-limb's motion to perform daily activity.

In active assist mode of rehabilitation, neuro-fuzzy based biological controller is used to trigger the robotic exoskeleton. In this biological control mode, EMG signals from shoulder and elbow muscles and the force generated between the exoskeleton robot and subject's wrist is used as input information to build a part of total architecture's of this controller. The controller is said as *biological controller* due to the dominating input signals (i.e., EMG signals) to the controller which is biologically generated), and is comprises of *force sensor based controller* (FBC) and *EMG based controller* (EBC) coupled with *obstacle avoidance controller* (OAC).

Fuzzy-neuro control method, which is a combination of flexible fuzzy control and adaptive neural network control, has been applied to realize the sophisticated real time control of the exoskeleton robot [2]. Note that, an obstacle avoidance controller (OAC) is coupled with integrated FBC and EBC to provide robotic exoskeleton desired motion of assisting upper-limb and rehabilitation and also to avoid collision between the robotic exoskeleton arm and the frame of the

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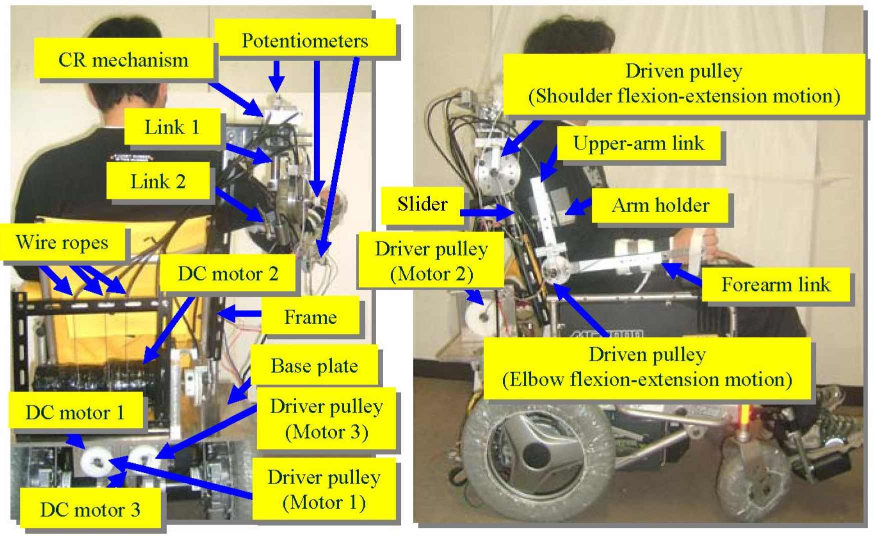


(a) Rear View (b) Side View

Fig. 1 Mobile Exoskeleton Robot

wheel chair (i.e., on which the exoskeleton robot system is installed).

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

II. Robotic Exoskeleton

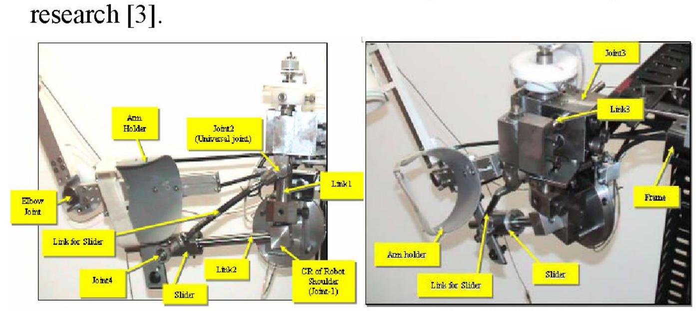
The robotic exoskeleton, as shown in Fig.1, consists of a shoulder motion support part, an elbow motion support part, and a mobile wheel chair. Considering the design criteria, e.g., light weight of exoskeleton, safety in operation, comfort of wearing, reliability in operation, wide and safety range of motion, relatively low complexity in design, real time force feedback and overall low or no maintenance cost; the robotic exoskeleton system (Fig.1) has been designed and developed [7] for rehabilitation and to assist upper limb motion of physically weaken persons. The mobile chair itself has 2DOF which provides an independent movement of physically weaken persons.

To assist shoulder motion, its 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)).

For generating 2DOF shoulder 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.

Upper arm link which is fixed with slider (Fig.1 (b)) carry the arm holder as well as the elbow motion support part also. 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. 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 as shown in Fig.2 is installed in between link1 and link2 of the robotic exoskeleton.

The shoulder joint (i.e., joint between the link1 and the link2) of the robotic exoskeleton is supposed to be located just behind the armpit of the robot user. This CR mechanism makes the CR of the robot 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. A detail about CR mechanism is explained in our previous research [3].



(a) Side view (b) Rear side view

Fig.2 Centre of Rotation mechanism

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In this exoskeleton system, 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.

1DOF elbow motion assist part of the exoskeleton robot system (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 driver pulley and pulley connected to the elbow joint (as shown 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.

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

Considering many physically weak persons use 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 -5° and 145° and that of human shoulder is 180° in flexion, 60° in extension, 180° in abduction and 75° in adduction. Considering the practical applications to everyday life and safety, the elbow motion is limited between 0° to 120° and that of shoulder motion is limited to 0° in extension and adduction, 90° in flexion, and 90° in abduction, in the proposed exoskeleton robot system. Note that, maximum movable range of the proposed exoskeleton robot system as stated earlier is kept by both hardware and software.

III. EMG Signal Processing and Muscles Model [6]

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 and it is very difficult to reduce noise by filtering. Furthermore, it is difficult to use raw EMG data as input information to the controller. Therefore, features have to be extracted from the noisy raw EMG data. Among various features extraction method, e.g., mean absolute value, average rectified value, mean absolute value slope, root mean square (RMS), zero crossing, waveform length or slope sign changes, we have preferred RMS values to process raw EMG signals. 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 [9] for measuring 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.3) of the users are monitored and used as input information to control the exoskeleton robot system [2].

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.

IV. Exoskeleton Robot Controller

A. *Passive mode of Rehabilitation:*

In the scheme of passive mode of rehabilitation, users/ subjects operate a 3DOF upper limb prototype motions indicator (Fig.4) by his/her hand to control the motion of the robotic exoskeleton systems. Joint kinematics of the robotic exoskeleton are fed to the controller to control the exoskeleton robot and thus providing passive mode of rehabilitation as well as assists the upper-limb's motion to perform daily activity. The reliable PD control has been applied for this controller. The outputs of the controller are the joint torque commands for shoulder and elbow joint of the robotic exoskeleton system, required to assist subject's upper-limb motion and also to perform rehabilitation therapy.

$$\tau_{sh} = K_{v\_sh}(\dot{\theta}_{d\_sh} - \dot{\theta}_{sh}) + K_{p\_sh}(\theta_{d\_sh} - \theta_{sh}) \tag{2}$$

$$\tau_{sv} = K_{v\_sv}(\dot{\theta}_{d\_sv} - \dot{\theta}_{sv}) + K_{p\_sv}(\theta_{d\_sv} - \theta_{sv}) \tag{3}$$

$$\tau_{e} = K_{v\_e}(\dot{\theta}_{d\_e} - \dot{\theta}_{e}) + K_{p\_e}(\theta_{d\_e} - \theta_{e}) \tag{4}$$

where, τ is the desired torque command (output of the controller), θ_d is the desired trajectory to follow generated by the motion indicator, θ is the measured joint angles of the exoskeleton robot, K_v and K_p are the gains for angular velocity error and angle error respectively. Note that subscript `*e*`,`*sh*` and `*sv*` of equations (2)-(4) denotes the elbow, shoulder horizontal and shoulder vertical angle of the exoskeleton robot, respectively.

B. *Active Assist mode of Rehabilitation:*

Proposed biological controller is responsible for active assist mode of rehabilitation as well as to assist daily upper limb motion of physically disabled or elderly persons. Based on input signals, initially the biological controller is categorized, into *force sensor based controller* (FBC) and *EMG based*

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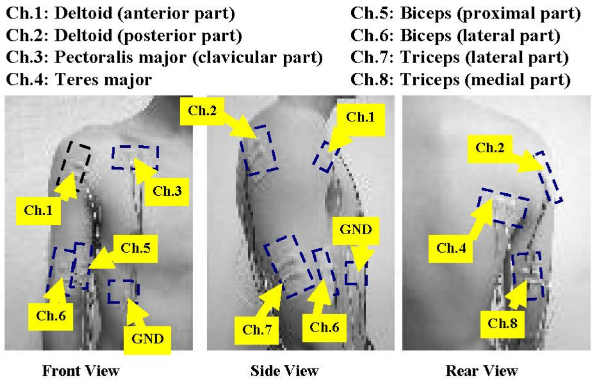


Fig. 3 Location of electrodes

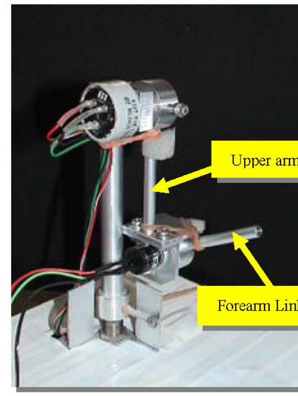


Fig.4. A 3DOF Upper-limb prototype motion indicator.

controller (EBC) and later FBC and EBC is integrated and coupled with *obstacle avoidance controller* (OAC) to form a total biological or automatic controller. In *biological control* mode, EMG signals from shoulder and elbow muscles and the force generated between the exoskeleton robot and subject's wrist (i.e., generated wrist force) is used as input information to build a part of total architecture's of this controller.

- *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, required to assist subject's upper-limb motion.

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

where, τ_d is the desired joint torque, J is the Jacobian, and f_w is the generated wrist forces. However, control is carried out based on the EMG signals (i.e., by EBC), when exoskeleton robot user's upper-limb muscles activity level is high (i.e., when the EMG levels of the subject is high). When the muscle activity level of robot users is low (i.e., when the EMG levels of the subject is low), control is carried out based on the wrist force sensor signals (i.e., FBC). In the intermediate activity level of muscles both EBC and FBC acts simultaneously.

- *EMG Based Controller (EBC [10]:*

In EBC, the initial fuzzy IF-THEN control rules are designed based on the analyzed human shoulder and elbow motion patterns in the pre-experiment [3], [5] and then transferred to the neural network form. However, 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 [2]. To overcome from this problem, multiple neuro-fuzzy controllers have been designed and applied under certain arm posture region. Based on the movable range of joint angles, elbow motion is divided into three regions and that of shoulder motion is divided into nine regions, where distinct neuro-fuzzy controller is applied. More details about the controllers are explained in [2].

A total of 21 rules are prepared (ten rules for shoulders and eleven rules for elbow) for each neuro-fuzzy controller. 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.5. Here $\sum$ means summation of inputs and $\prod$ means multiplication of inputs. Two kinds of nonlinear functions (f_G and f_S) are prepared to express the membership function of the antecedent part of the neuro-fuzzy controller.

$$f_s(\mu_s) = \frac{1}{1+e^{-\mu_s}} \tag{6}$$

$$\mu_s(x) = w_o + w_i x \tag{7}$$

$$f_G(\mu_G) = e^{-\mu_G^2} \tag{8}$$

$$\mu_G(x) = \frac{w_o + x}{w_i} \tag{9}$$

where, w_o is the threshold value and w_i is the weight. For generating shoulder motion, the output of the neuro-fuzzy controller is the torque command and that of for generating elbow motion are the desired joint angle and impedance of the exoskeleton robot. Details about the impedance control are explained in our previous research [2].

Output of the integrated FBC and EBC thereafter used to derive the instantaneous robot end-effector force vectors (IREFV). The equation of derived IREFV is written as:

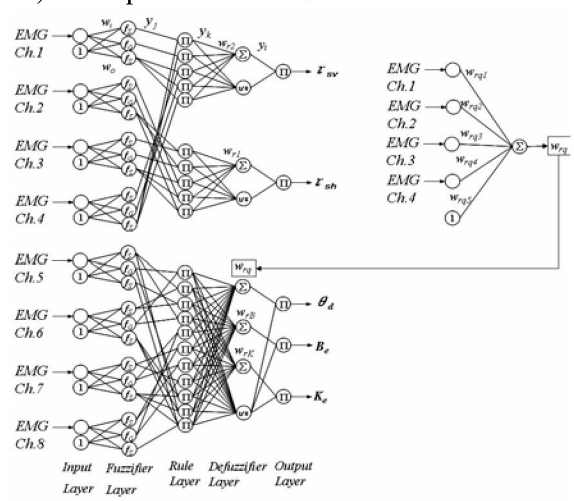


Fig. 5.Neuro-fuzzy controller

$$F_I = \tau / J^T \tag{10}$$

where, F_I is the IREFV and τ is the projected torque command generated from integrated FBC and EBC.

Average force vectors (AFV) are then calculated by sampling the preceding force vectors (i.e., excluding the IREFV) at a rate 200msec. IREFV is then compared with the preceding AFV and a mean of this two is calculated which is the command end-effector force vectors to generate the desired joint torques of the robotic exoskeleton [10]. The equation of AFV, command force vectors and desired joint torques are listed below:

$$AFV = \frac{1}{N}\sum_{i=1}^{N} F_i \tag{11}$$

$$F_C = (F_I + AFV)/2 \tag{12}$$

$$\tau_d = J^T F_C \tag{13}$$

where, F_i is the IREFV at the i^{th} sampling, N is the number of sample in a segment, F_C is the command force vectors and τ_d is the desired joint torques. The torque command for the exoskeleton robot joint is then transferred to the torque command to the driving motors.

Since our robotic exoskeleton is installed on a mobile wheel chair, integrated EBC and FBC should be coupled with any OAC to avoid unexpected collision with the frame of wheel chair. For this to achieve, virtual repulsive force field is created by the combination of virtual spring and damper [10], on the obstacle surfaces so that when robotic exoskeleton reach near to obstacles it is pushed back by the virtual repulsive forces and thus allow the robotic exoskeleton to avoid collision with obstacles [10].

V. EXPERIMENT

Experiment has been performed with healthy male human subjects to evaluate the effectiveness of the proposed passive and active assist mode of rehabilitation scheme. The experimental set-up is shown in Fig.6 For passive mode of rehabilitation, the subjects operate a 3DOF upper limb prototype motions indicator (Fig.4) by his/her hand to indicate the desired trajectory to follow. Figure 7 shows an approach of passive mode of rehabilitation performed by the motion indicator. In this figure, green line stands for the RMS value of EMG, blue line stands for measured angle of rotation of robotic exoskeleton joints, and black line stands for desired angle of rotation of robotic exoskeleton joints indicated by the motion indicator. It seems from these figures that robotic exoskeleton can follow the desired trajectory indicated by the motion indicator. Thus satisfies the condition of passive mode of rehabilitation. Here only the experimental results of ch.1, ch.2 and ch.5 with shoulder vertical, shoulder horizontal and elbow angle respectively are given, since anterior part of deltoid (ch.1), posterior part of deltoid (ch.2) and proximal part of biceps (ch.5) activates highly with the shoulder vertical, shoulder horizontal and elbow angle respectively.

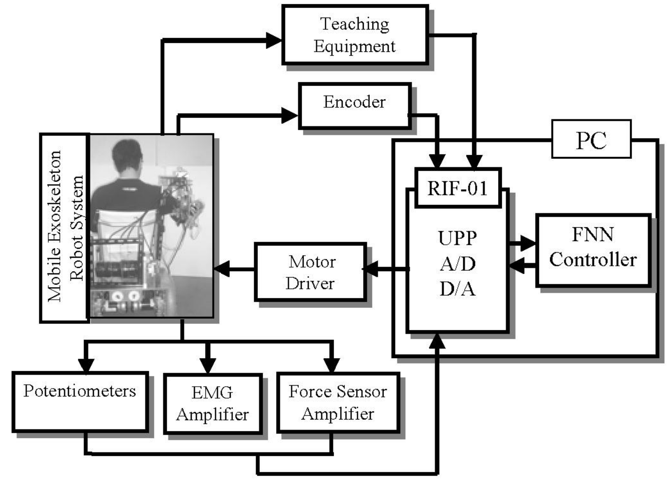
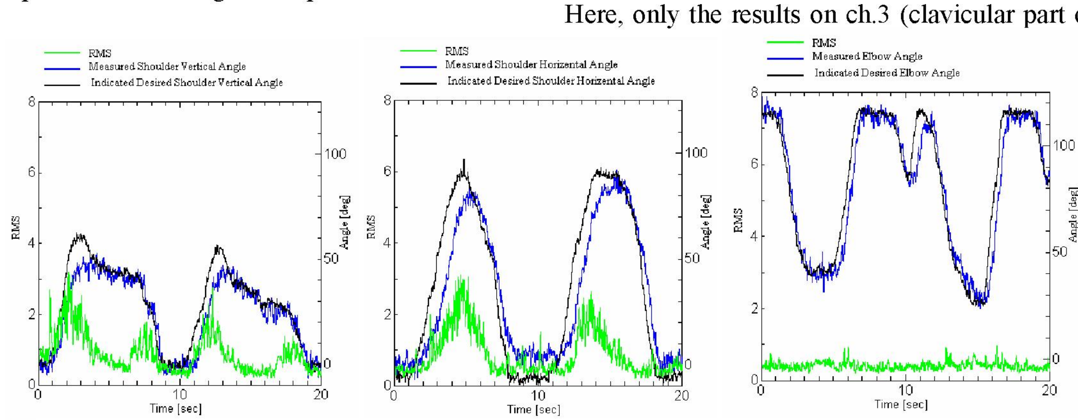


Fig. 6 Experimental set-up

For active assist mode of rehabilitation and also to evaluate the effectiveness of biological controller regarding to motion assist a co-operative motion of upper limb is performed by biological controller (i.e., integrated FBC and EBC coupled with OAC) with and without assist of exoskeleton robot. Fig.8 and Fig.9 show the experimental results with and without assist of the exoskeleton robot system, respectively.

Here, only the results on ch.3 (clavicular part of pectoralis



(a) Anterior part of deltoid (b) Posterior part of deltoid (c) Proximal part of biceps

Fig.7 Experimental results of passive mode of rehabilitation

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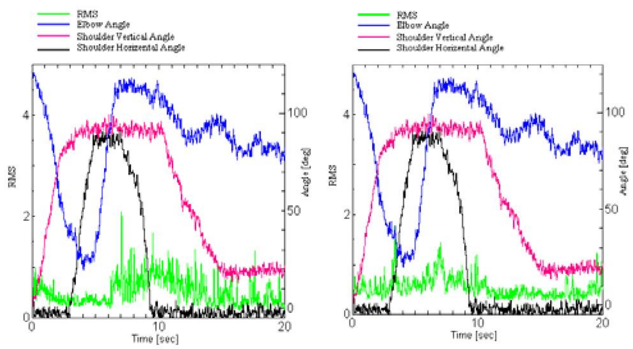
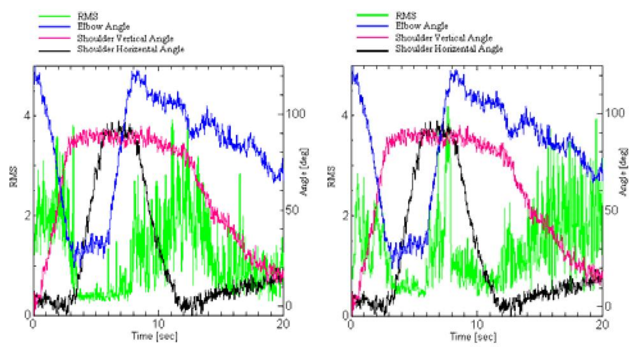


(a) Pectoralis major (clavicular part) (b) Biceps (lateral part)

Fig. 8 Experimental result with assist of robotic exoskeleton



(a) Pectoralis major (clavicular part) (b) Biceps (lateral part)

Fig. 9 Experimental result without assist of robotic exoskeleton

major), and ch.6 (lateral part of biceps) are shown since they are the one of the active muscles among the shoulder and elbow muscles. Comparing Fig..8 with Fig.9, it may conclude that with assist of biological controller subject is able to trace the desired trajectory to follow (i.e, trajectory generated with and without assist of robotic exoskeleton are almost same). Thus satisfies the condition of active assist mode of rehabilitation. Also comparing Fig.8 with Fig.9, we may conclude, RMS values (muscles activity) are much lower when subject motion is assisted by the proposed exoskeleton robot.

VI. Conclusion

Mechanism and actuation system of mobile robotic exoskeleton for rehabilitation and for assisting upper-limb motion of physically weaken persons was described. Effectiveness of the proposed rehabilitation (i.e., passive and active assist mode of rehabilitation) and motion assist scheme for elderly or physically disabled persons has been evaluated by experiment.

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