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Motion Control of a Robotic Exoskeleton

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***Abstract*— Physical disabilities such as full or partial loss of function in shoulder, elbow or wrist is a common ailment due to geriatric disorder and other disease processes. To assist such physically disabled and or elderly people, we have been developing a 3DOF mobile exoskeleton robot 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 exoskeleton robot is mainly activated and is controlled by the skin surface electromyogram (EMG) signals, since EMG signals of muscles directly reflect how the subject intends to move. In this paper, we propose neuro-fuzzy based motion control with obstacle avoidance behavior of a robotic exoskeleton for rehabilitation and assisting motion of upper-limb of physically disabled or elderly persons.**

I. INTRODUCTION

THE 21st century is an era of geriatric disorders. The numbers of aged peoples are increasing at an alarming rate in some countries. In Japan, the number of persons aged 65 and over has reached a record 24.31 million, accounting for 19% of the total population. The number is 0.5% higher from a year earlier and the highest among industrialized nations. In addition to geriatric disorders, physical disabilities such as full or partial loss of function in shoulder, elbow or wrist is also appears due to disease processes including trauma, sports injuries, occupational injuries, spinal cord injuries, and strokes.

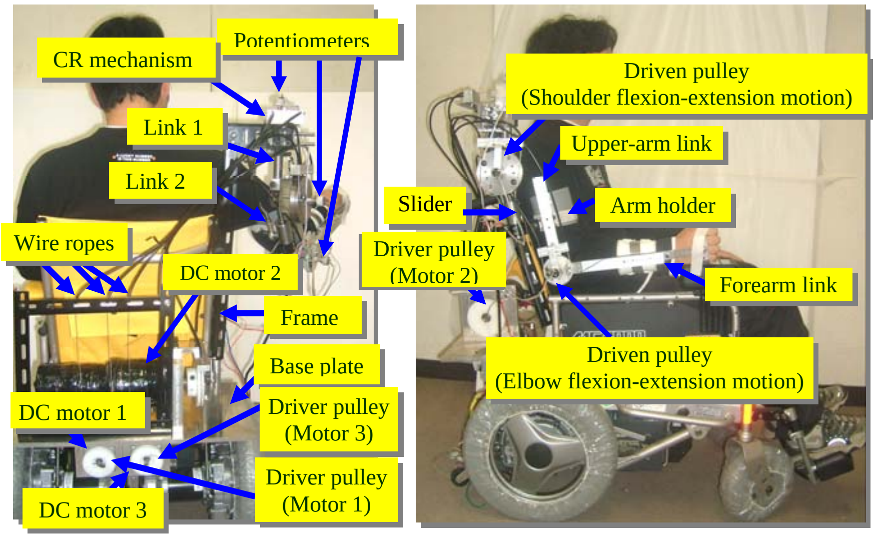
To assist elderly people or disabled people who have lost their body functioning of motion, extensive research has been carried out [1]-[9] in many branch of welfare robotics to compensate for their lost functions for providing an independent life and play a more productive role in society. Exoskeleton robot is one of the outstanding products of new assistive technology of welfare robotics.

Since human shoulder and elbow motions are used in a lot of activities of everyday life, we have been developing exoskeleton robot for rehabilitation and for assisting motion of elbow [4], [5] and shoulder [3] of the elderly or physically weak persons so that they can perform their daily tasks properly.

During the first generation [1] of exoskeleton research kinematical-position command was used to control the robot [6], thereafter during the second generation [1] of exoskeleton research dynamic-contact force command [13] is used to trigger the exoskeleton robot. However, both these events constitute a source of delay [1] in the systems. One of the leading ideas for the new generation of exoskeleton research is to use directly human physiological signal to control the exoskeleton robot. During the movement or motion of any limbs of human body, neural system activates the muscular system. Skin surface electromyogram (EMG) signals contain those information of muscular system and directly reflects how the user intends to move. The EMG signals are important information for this type of robotic systems. Therefore, exoskeleton robot is able to assist the motion of the user effectively by applying the user's EMG as input signals to the robot controller.

In this paper, we proposed motion control of a 3DOF robotic exoskeleton for rehabilitation and motion assist in daily activity for physically weaken persons. This 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. This paper named the controller as *biological controller* (which comprises of *force sensor based controller* (FBC) and *EMG based controller* (EBC) coupled with *obstacle avoidance controller* (OAC)) based on the dominating input signals to the controller which is biologically generated (EMG signals). EMG signals from shoulder and elbow muscles and generated wrists forces are used as input parameters to build a part of total architecture of this controller. Control is carried out based on the EMG signals, 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. In addition to provide active assist mode of rehabilitation the proposed biological controller is responsible to assist the upper-limb's motions to perform daily activity.

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]. Considering all the possible aspects of input signals effective knowledge based multiple fuzzy-neuro controllers are designed and integrated with FBC by the membership function prepared from EMG



(a) Rear View (b) Side View

Fig. 1 Mobile Exoskeleton Robot

signals. Integrated FBC and EBC thereafter coupled with obstacle avoidance controller (OAC) 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 wheel chair (i.e., on which the exoskeleton robot system is installed).

An obstacle avoidance controller is required to allow the robot and or robotic manipulators to safely travel at high speeds. A variety of concepts has been developed in the literature of obstacle avoidance. In 1985, Khatib presented the concept of *artificial potential fields*, which was the first real-time obstacle avoidance algorithm for mobile robots as well as for manipulators [10]. Around the same time, Moravec and Elfes pioneered the concept of *certainty grids*, a widely popular map representation that is well suited for sensor data accumulation and sensor fusion [12]. Borenstein and Koren later developed the concept of *Virtual Force Field* method by integrating the concept of potential fields with the concept of certainty grids [11]. Obstacle avoidance controller applied for this study, takes the principles of developing *artificial potential fields* around the obstacles. In this scheme of OAC, a virtual repulsive force field is developed by using virtual spring and damper combination on the two layer virtual wall surfaces which is pre-defined to cover the frame of the wheel chair. When robotic exoskeleton reaches near to obstacles it feels pushing back by the virtual repulsive forces and thus allow the manipulator to avoid collision with obstacles.

In next section of this paper, an overview of the development of exoskeleton robot is presented. Features of 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.

II. ROBOTIC EXOSKELETON

Considering design criteria such as light weight of exoskeleton to provide low mass moment of inertia, 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 maintenance cost; we have designed 3DOF mobile exoskeleton robot system for rehabilitation and to assist upper limb motion [9].

The mobile exoskeleton robot system as shown in Fig.1 consists of a shoulder motion support part, an elbow motion support part, and a mobile wheel chair. 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.

The CR mechanism (Fig.1 (a)) is explained explicitly in our previous research [3], consists of a slider (made of ball-spline mechanism) and two links (link1 and link2, as shown in Fig.1 (a)). Upper arm link which is fixed with slider (Fig.1 (b)) carry 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 subject's upper arm. The manipulation of subject'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.

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.

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

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:

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

where, v_i is the voltage value at the kth 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.

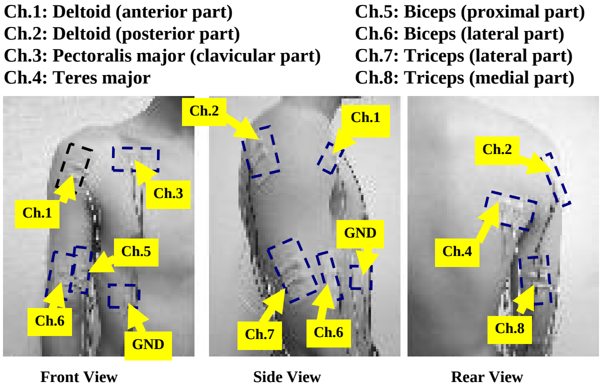


Fig. 2. Location of electrodes

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 [14] 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.2) 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

This controller is responsible to provide active assist mode of rehabilitation as well as to assist the upper-limb's motions of a physically weaken persons to perform daily activity. Based on input signals, initially the proposed controller is categorized, into *force sensor based controller* (FBC) and *EMG based controller* (EBC) and later FBC and EBC is integrated and coupled with *obstacle avoidance controller* (OAC) to form a total biological or automatic controller. Figure 3 shows the schematic diagram of biological 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. Selection of the controller for desired motion of assist is depends on input signals and usually obeys the following principles.

- *Input signals:*

Proper input information for the controller is selected based on the user's muscles activation level. Control is carried out based on the EMG signals, when exoskeleton robot user's upper-limb muscles activity level is high (i.e., when the EMG levels of the subject is high). However 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.

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

$$\tau_d = J^T f_w \tag{2}$$

where, τ_d is the desired joint torque, J is the Jacobian, and f_w is the generated wrist forces.

B. EMG Based Controller (EBC):

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 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. 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. 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 robot users by adjusting all of antecedent part and some of the consequent part of the controllers by using the back propagation learning algorithm.

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.4. Here Σ means summation of inputs and Π 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.

$$f_s(\mu_s) = \frac{1}{1+e^{-\mu_s}} \tag{3}$$

$$\mu_s(x) = w_o + w_i x \tag{4}$$

$$f_G(\mu_G) = e^{-\mu_G^2} \tag{5}$$

$$\mu_G(x) = \frac{w_o + x}{w_i} \tag{6}$$

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]. The torque command for the exoskeleton robot joint is then transferred to the torque command to the driving motors.

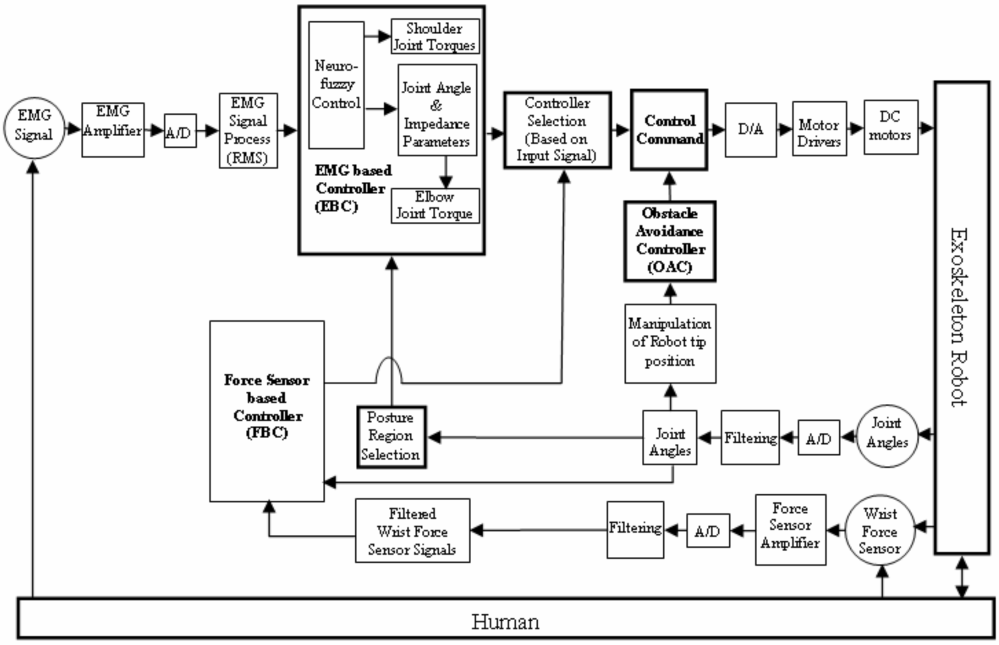


Fig. 3. Schematic diagram of *Biological or Automatic controller.*

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, on the obstacle surfaces so that when robotic exoskeleton reach near to obstacles it is back by the virtual repulsive forces and thus allow the manipulator to avoid collision with obstacles.

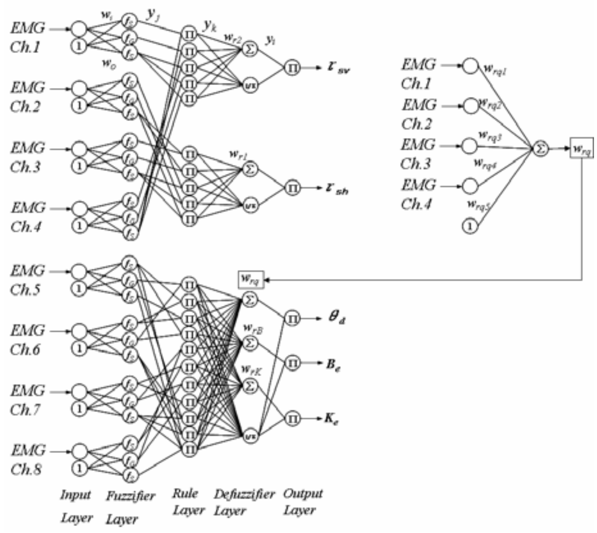


Fig. 4.Neuro-fuzzy controller

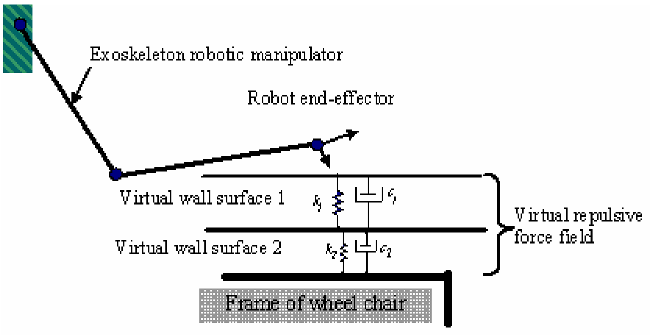


Fig. 5. Structure of robotic exoskeleton and virtual obstacle

A two layer virtual wall (as a virtual obstacle) is created to cover the frame of wheel chair (Fig.5. Between *virtual wall surface 1* and *2*, relatively soft spring and damper is chosen compare to those in between *virtual wall surface 2* and virtual obstacle (i.e., frame of wheel chair) to exert a relatively low repulsive forces when robotic exoskeleton knock the *virtual wall surface 1*. However, exoskeleton robot tip subjects to strong repulsive forces when it knocks to *virtual wall surface 2*. The equation of virtual repulsive force is written as:

$$F = k(x_{wall\_surface} - x_{tip}) + c(\dot{x}_{wall\_surface} - \dot{x}_{tip}) \qquad (7)$$

where, F is the virtual repulsive force, k is the spring constant, c is the damping constant, $x_{wall\_surface}$ is the virtual wall surface and x_{tip} is the instantaneous robot tip position inside the virtual wall surface. In this study, spring and damping constant for soft spring and damper combination is chosen (by experiment) 100N/m and 0.5Nsec/m, respectively and those for hard spring and damper combination is chosen (by experiment) 130N/m and 0.8Nsec/m, respectively. Torque generated due to virtual repulsive force is expressed by the following equation.

$$\tau_{rep} = J^T F \qquad (8)$$

where, τ_{rep} is the joint torques due to repulsive virtual forces.

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-up is shown in Fig.6. In this experiment, upper limb motion is performed by biological controller (i.e., integrated FBC and EBC coupled with OAC) with and without assist of exoskeleton robot. Fig.7 and Fig.8 show the experimental results with and without assist of the exoskeleton robot system, respectively.

Here, only the results on ch.1 (anterior 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. Comparing Fig.7 with Fig.8, it may conclude that RMS values (muscles activity) are much lower when subject motion is assisted by the proposed exoskeleton robot. In order to evaluate the effectiveness of the biological controller (i.e., integrated FBC and EBC coupled with OAC) regarding to obstacle avoidance, another experiment has also been carried out wearing robotic exoskeleton by performed motion near the contour of the virtual wall surfaces as well as virtual obstacle.

Figure 9 (a) and (b) show two different approaches (co-operative motion of shoulder & elbow joint) of robotic exoskeleton motion near the virtual obstacle. Here the experimental results of ch.8 (medial part of triceps) are shown since triceps activates more among all muscles when subject knock at the virtual wall. It comes out from the Fig.9 that the motion of the exoskeleton robot is restricted when

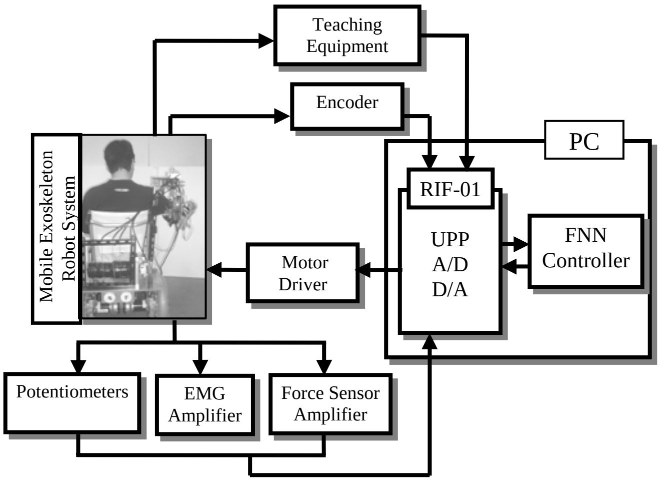
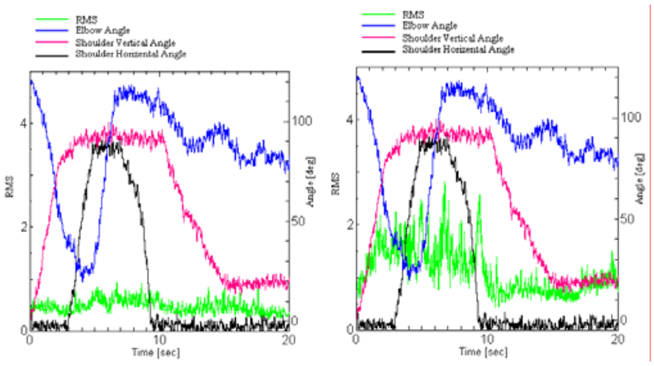
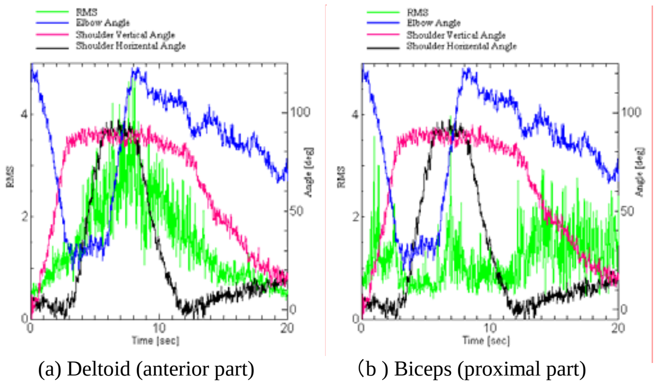


Fig. 6. Experimental set-up



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

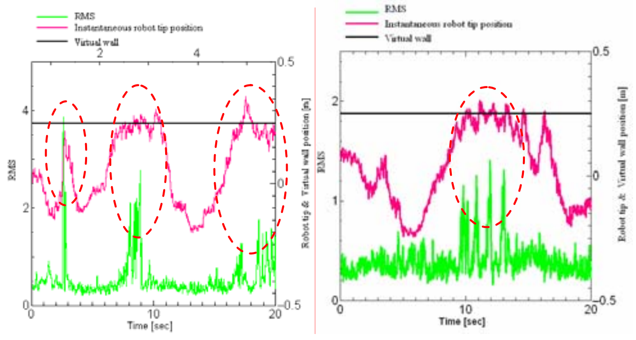
Fig. 7. Experimental result with assist of robotic exoskeleton



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

Fig. 8. Experimental result without assist of robotic exoskeleton

robot end-effector tried to impinge to the virtual wall. Also it reveals from above figure that RMS value of muscle (ch.8, medial part of triceps) is increased near at virtual wall since subject tried to knock the wall.



(a) Motion 1 (b) Motion 2

(Ch.8 Triceps medial part)

Fig. 9. Effect of obstacle avoidance controller.

VI. CONCLUSION

The mechanical and actuation system of the proposed mobile robotic exoskeleton for rehabilitation and for assisting upper-limb motion of physically weaken persons was described. Effectiveness of the proposed biological controller (i.e., integrated *force sensor based controller* and *EMG based controller* coupled to *obstacle avoidance controller*) for motion assist and obstacle avoidance has been evaluated by experiment. The experimental result shows the effectiveness of the proposed OAC coupled to FBC and EBC.

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