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Design and Control of an Exoskeleton System for Human Upper-Limb Motion Assist

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Abstract

In this paper, we introduce a 3 DOF exoskeleton system to assist the human upper-limb motion (shoulder flexion-extension motion, shoulder adduction-abduction motion, and elbow flexion-extension motion) for daily activity and rehabilitation. The electromyogram (EMG) signals of human muscles are important signals to understand how the patient intends to move. The proposed exoskeleton automatically assists the patient's motion for daily activity and rehabilitation mainly based on the skin surface EMG signals. Even though the EMG signals contain very important information, however, it is not very easy to predict the patient upper-limb motion (elbow and shoulder motion) based on the EMG signals in a short time because of the difficulty in using the EMG signals as the controller input signals. In order to cope with this problem, fuzzy-neuro control has been applied to realize the sophisticated real-time control of the exoskeleton system for motion assist of the patient. Experiment has been performed to evaluate the proposed exoskeleton and its control system.

INTRODUCTION

Recent progress in robotics and mechatronics technology brings a lot of benefits not only in the field of industries, but also in the fields of welfare and medicine. Although active orthotic systems [1][2], which are similar to the exoskeletal systems, have been studied for handicapped persons from the 1960s, the advanced robotics and mechatronics technology were not actively applied to them. Therefore, the users had to learn how to control the systems in order to use these orthotic systems because of the primitiveness of their controllers. We have been developing exoskeleton systems [3]-[5] in order to automatically assist the motion of physically weak persons such as elderly persons, handicapped persons, and injured persons. In this paper, we introduce a 3 DOF exoskeleton system to automatically assist the human upper-limb motion (shoulder flexion-extension motion, shoulder adduction-abduction motion, and elbow flexion-extension motion) for daily activity and rehabilitation.

The electromyogram (EMG) signals of human muscles are important signals to understand how the patient intends to move. The EMG signals can be used as input information for the control of robotic systems [6]-[8]. The proposed exoskeleton system automatically assists the patient's motion for daily activity and rehabilitation mainly based on the skin surface EMG signals. Even though the EMG signals contain very important information, however, it is not very easy to predict the patient upper-limb motion (elbow and shoulder motion) based on the EMG signals in a short time since many muscles are involved in the motion. Furthermore, it is difficult to obtain the same EMG signals for the same motion even from the same patient since the EMG signal is a biological signal which is affected by the physical and physiological condition of the patient, besides each patient might use the muscles in a different way to generate the same motion. Moreover, the level of the EMG signals might be much different between patients. Therefore, the exoskeleton system must have an ability to adapt itself to the physical and physiological condition of each patient. In order to cope with this problem, fuzzy-neuro control has been applied to realize the sophisticated real-time control of the exoskeleton system for motion assist of the patient. The fuzzy-neuro controller is supposed to control the elbow and shoulder joint angles of the exoskeleton system based on the amount of the skin surface EMG signals of arm and shoulder muscles and the generated wrist force.

In this paper, we also propose an efficient adaptation evaluation method for the fuzzy-neuro controller. In the proposed controller adaptation process, the assist level (the support level) can be adjusted until the amount of patient's EMG signals of arm and shoulder muscles becomes the desired level. The desired EMG levels of the muscles are decided for each patient based on his/her physical and physiological condition. Consequently, the desired amount of power assist can be realized for each patient. Experiment has been performed to evaluate the proposed exoskeleton and its control system.

EXOSKELETON SYSTEM

The proposed exoskeleton system is supposed to be attached to the lateral side of a patient directly. The architecture of the exoskeleton system is shown in Fig. 1. The exoskeleton system consists of four main links (two links for shoulder joint motion and another two links for elbow joint

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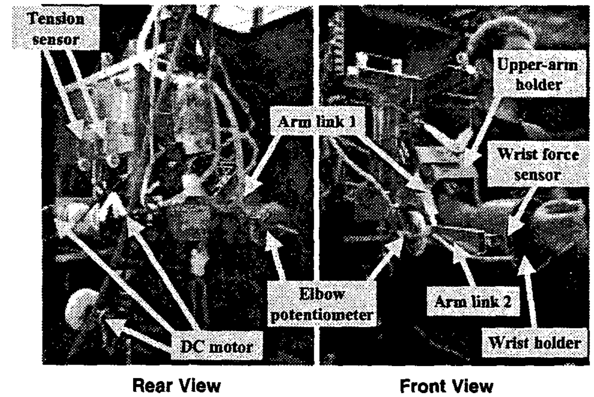
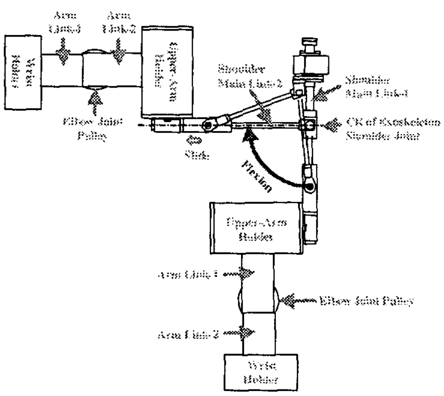
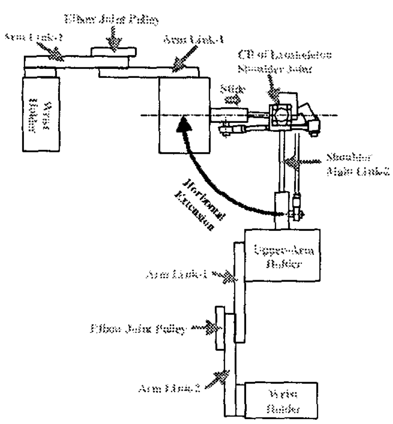


(a) Attached exoskeleton



(b) Architecture (Side view)



(c) Architecture (Top view)

Figure 1. Architecture of the exoskeleton system

motion), a frame, three DC motors, an upper-arm holder, a wrist force sensor, driving wires, wire tension sensors, and driving motors. An air cushion is attached inside of the upper arm holder. By adjusting the air pressure of the air cushion, the upper arm holder can be properly attached to the upper arm of any patient. The shoulder vertical and horizontal flexion-extension of the patient (see Fig. 2) are assisted by the exoskeleton system by activating the upper arm holder, which is attached on the main link-2 for shoulder joint motion, using driving wires driven by two DC motors. The shoulder angle is measured by potentiometers attached to the link-1 and link-2 of the exoskeleton. The wire tension (driving force) is measured by the wire tension sensors. The signals from the sensors are sampled at a rate of 2kHz (the EMG signals are also sampled at the same time) and low-pass filtered at 8Hz.

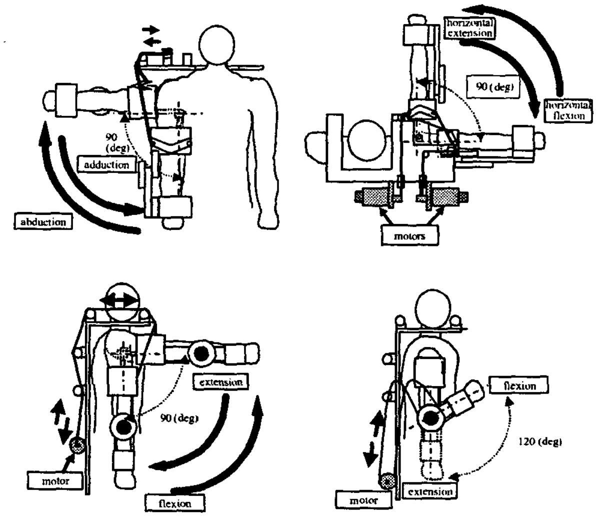
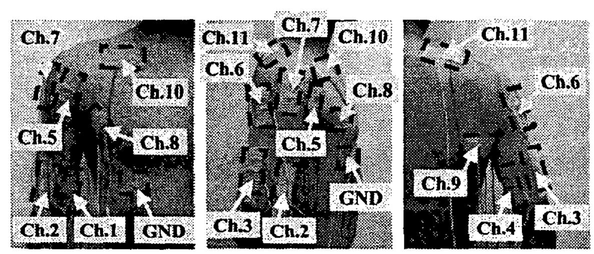


Figure 2. Motion of the exoskeleton system

The elbow flexion-extension motion of the patient (see Fig. 2) is assisted by the exoskeleton system by activating the elbow joint pulley using the driving wire. In order to make the movable links light weight, DC motors are fixed on the frame.

Human elbow joint is mainly activated by biceps and triceps, and moves in 1 DOF. Human shoulder joint is activated by many muscles such as deltoid, pectoralis major, teres major, and trapezius, and moves in 3 DOF. In this study, EMG

Ch.1: Biceps (proximal part)
Ch.2: Biceps (lateral part)
Ch.3: Triceps (lateral part)
Ch.4: Triceps (proximal part)
Ch.5: Deltoid (anterior part)
Ch.6: Deltoid (posterior part)
Ch.7: Deltoid (middle part)
Ch.8: Pectoralis major
Ch.9: Teres major
Ch.10: Pectoralis major (clavicular part)
Ch.11: Trapezius



Front view **Side view** **Rear view**

Figure 3. Location of electrodes

signals of biceps (lateral and proximal parts), triceps (lateral and proximal parts), deltoid (anterior, middle, and posterior parts), pectoralis major (lateral and clavicular parts), teres major, and trapezius (see Fig. 3) are measured and used for control of the proposed exoskeleton system.

Usually, the limitation of the movable range of human elbow is between –5 and 145 degrees and that of human shoulder are 180 degrees in flexion, 60 degrees in extension, 180 degrees in abduction, and 75 degrees in adduction. Considering the minimally required motion in everyday life and the safety of the parient, the elbow joint motion of the proposed exoskeleton system is limited between 0 and 120 degrees, and the limitation of the shoulder joint motion of the proposed exoskeleton system are decided to be 0 degrees in extension and adduction, 90 degrees in flexion, and 90 degrees in abduction.

NEURO-FUZZY CONTROLLER

A fuzzy-neuro controller, a combination of a flexible fuzzy controller and an adaptive neuro controller, has been applied as a controller for the proposed exoskeleton system in this study. The initial fuzzy IF-THEN control rules are designed based on the analyzed human elbow and shoulder motion patterns in the pre-experiment, and then transferred to the neural network form. The EMG characteristics of human elbow and shoulder muscles studied in another research [9]-[12] are also taken into account.

In the proposed control method, the definition of the antecedent part of the fuzzy IF-THEN control rules for elbow motion is adjusted based on the activation level of shoulder muscles, since the amount of the EMG signals of biceps is affected by shoulder motion. The effect of the arm posture change is also taken into account in the controller [4][5], since the arm posture change affects the amount of the EMG signals generated for the joint motion. In the proposed fuzzy-neuro controller, there are 16 rules (3 patterns) for elbow motion, 32 rules for shoulder motion, and 2 rules for controller switching between the EMG based control and the wrist force sensor based control. The simplified proposed control architecture is depicted in Fig. 4 and the architecture of the fuzzy-neuro controller is depicted in Fig. 5. Here Σ means sum of the inputs, Π means multiplication of the inputs. Two kinds of nonlinear functions (f_G: Sigmoidal function and f_S: Gaussian function) are applied to express the membership function of the fuzzy-neuro controller.

In order to extract the features from the raw EMG signals, the MAV (Mean Absolute Value) is calculated and used as input signals to the fuzzy-neuro controller. The equation of the MAV is written as:

$$MAV = \frac{1}{N}\sum_{k=1}^{N}|x_k| \qquad (1)$$

where x_k is the voltage value at kth sampling, N is the number of samples in a segment. The number of samples is set to be 100 and the sampling time is set to be 1ms in this study.

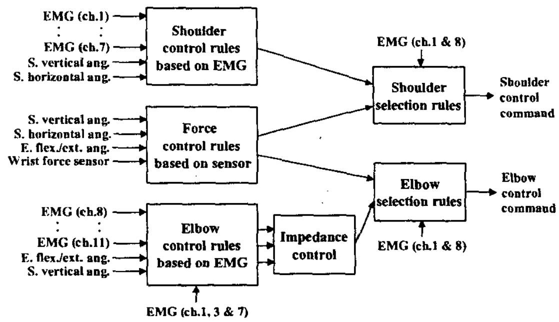


Figure 4. Controller architecture

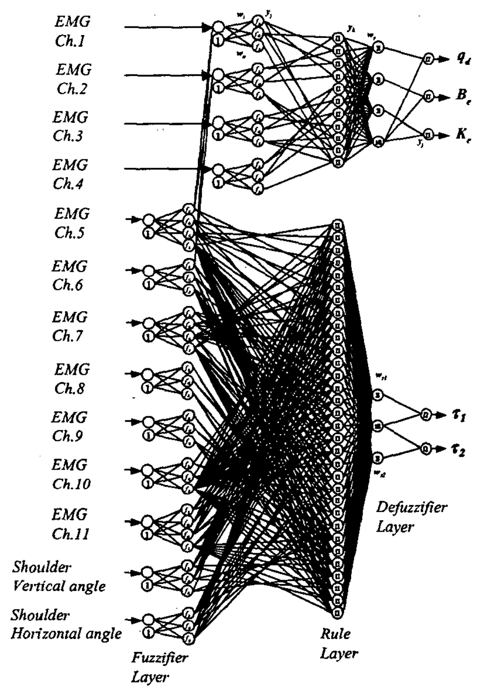


Figure 5. Architecture of the fuzzy-neuro controller

The input variables of the fuzzy-neuro controller are the MAV of EMG of eleven kinds of muscles, elbow angle, shoulder angles (vertical and horizontal angles), and force signals from the wrist force sensor. Four kinds of fuzzy linguistic variables (ZO: zero, PS: positive small, PM: positive medium, and PB: positive big) are prepared for the MAV of EMG (ch. 1, 3, and 7). Three kinds of fuzzy linguistic variables (ZO, PS, and PB) are prepared for the MAV of EMG (ch. 2, 4-6, and 8-11). Three kinds of fuzzy linguistic variables (EA: Extended, FA: Flexed, and IA: Intermediate angle) for elbow and shoulder angles.

The outputs of the fuzzy-neuor controller are the torque command for shoulder motion, and the desired impedance parameters and the desired angle for elbow motion of the exoskeleton. The torque command for the shoulder joint of the exoskeleton is then transferred to the force command for each driving wire. The relation between the torque command for the shoulder joint of the exoskeleton and the force command for driving wires is written as the following equation:

$$\tau_s = J_s^T f_{sd} \quad (2)$$

where τ_s is the torque command vector for the shoulder joint of the exoskeleton system, f_{xd} is the force command vector for the driving wires, and J_s is the Jacobian which relates the exoskeleton's joint velocity to the driving wire velocity. Force control is carried out to realize the desired force (f_{sd}) in driving wires by the driving motors for shoulder motion of the exoskeleton system.

Impedance control is performed with the derived impedance parameters and the derived desired angle for the elbow joint control of the exoskeleton system. The equation of impedance control is written as:

$$\tau_e = M_e(\ddot{q}_d - \ddot{q}) + B_e(\dot{q}_d - \dot{q}) + K_e(q_d - q) \quad (3)$$

where τ_e denotes torque command for the elbow joint of the exoskeleton system, M_e is the moment of inertia of the arm link-2 and human subject's forearm, B_e is the viscous coefficient generated by the fuzzy-neuro controller, K_e is the spring coefficient generated by the fuzzy-neuro controller, q_d is the desired joint angle generated by the fuzzy-neuro controller, and q is the measured elbow joint angle of the exoskeleton system. The torque command for the elbow joint of the exoskeleton system is then transferred to the torque command for the driving motor for the elbow motion of the exoskeleton system.

CONTROLLER ADAPTATION

In the controller adaptation process, the assist level (the support level) can be adjusted until the amount of patient's EMG signals of the muscles becomes the desired level. The desired EMG levels of the muscles are decided for each patient based on his/her physical and physiological condition. The back-propagation learning algorithm has been applied for the controller adaptation. All of antecedent part and some of consequence part of the fuzzy IF-THEN control rules are adjusted during the controller adaptation process. The evaluation function for the controller adaptation is written as:

$$E_e = \frac{1}{2}((\theta_{e\_d} - \theta_e)^2 + \alpha\sum_{i=1}^{4}(MAV_{i\_d} - MAV_i)^2) \quad (4)$$

$$E_s = \frac{1}{2}((\theta_{s\_d} - \theta_s)^2 + \alpha\sum_{i=5}^{11}(MAV_{i\_d} - MAV_i)^2) \quad (5)$$

where θ_{e_d} and θ_{s_d} are the desired elbow and shoulder angle indicated by the teaching equipment, θ_e and θ_s are the measured elbow and shoulder angle, α is a coefficient which changes the degree of consideration of the muscle activity minimization, MAV_{i_d} is the desired muscle activity level in ch.*i*, and MAV_i is the measured muscle activity level in ch.*i*.

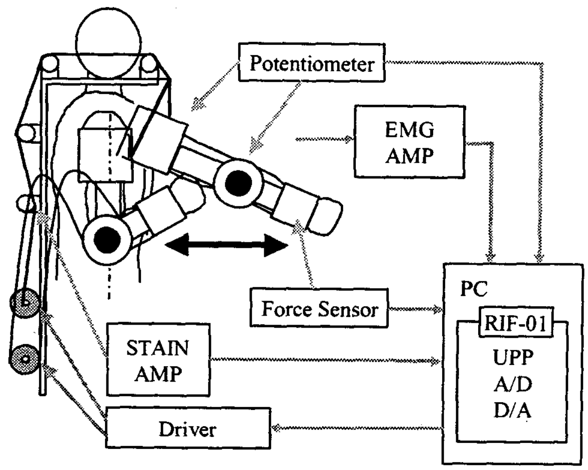


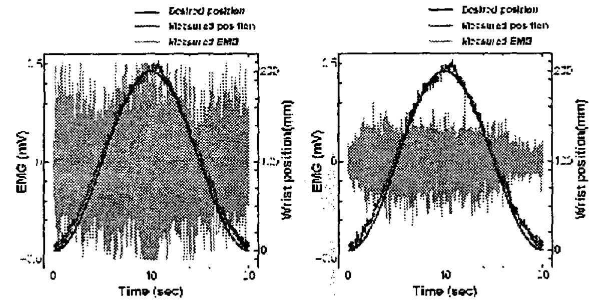
Figure 6. Experimental setup

By evaluating the amount of patient's EMG signals as well as the motion error in the evaluation function of the back-propagation learning algorithm during the upper-limb motion for the controller adaptation, the support level (the assist level) of the exoskeleton system can be adjusted until the amount of patient's EMG signals becomes the desired level.

EXPERIMENT

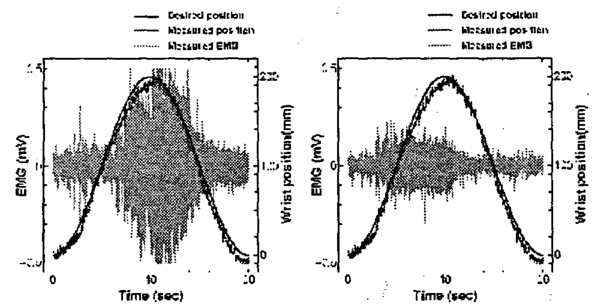
Motion assist experiment has been performed with three healthy human subjects (males; 22 years old) in order to evaluate the effectiveness of the proposed exoskeleton system. The experimental setup is shown in Fig. 6. In order to examine the effectiveness of the proposed exoskeleton system in motion assist for both the elbow and shoulder joint of the human subject, cooperative motion of the elbow and shoulder joints is performed in the experiment. In this motion, the human subject is supposed to move his wrist forward horizontally 200 [mm] from the initial position and backward again to the initial position following the target trajectory. The initial position of the upper-limb is set to be 0 [deg] in both horizontal and vertical flexion angle of the shoulder joint, and 120 [deg] in flexion angle of the elbow joint. The target wrist trajectory is 200sin(0.1πt) [mm]. All experiment is performed with and without the assist of the exoskeleton system for comparison. Two kinds of assist levels (low assist level and high assist level) are prepared. If the proposed exoskeleton system effectively assists the upper-limb motion, the activity levels of the EMG signals of the activated muscles are supposed to be reduced.

The experimental results of the subject A without the assist, with the low assist, with the high assistant of the proposed exoskeleton system are shown in Fig. 7 (a), (b), and (c), respectively. Only the results the EMG signals of ch. 1 (proximal part of biceps) and ch. 5 (anterior part of deltoid), which represent the elbow and shoulder muscles, are depicted here. The experimental results of the subject B and C are



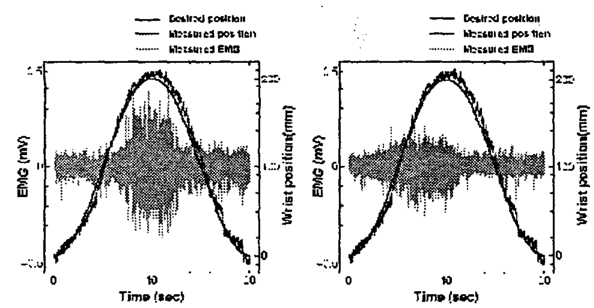
Proximal part of biceps (ch. 1) Anteror part of deltoid (ch5)

(a) without the assist



Proximal part of biceps (ch. 1) Anteror part of deltoid (ch5)

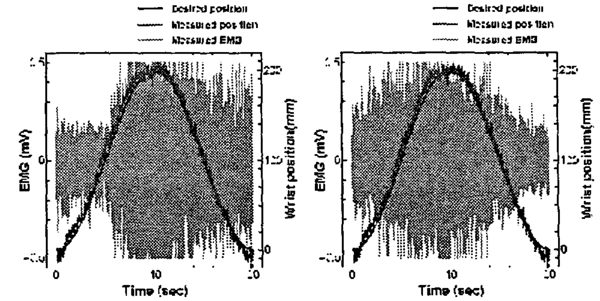
(b) with low assist



Proximal part of biceps (ch. 1) Anteror part of deltoid (ch5)

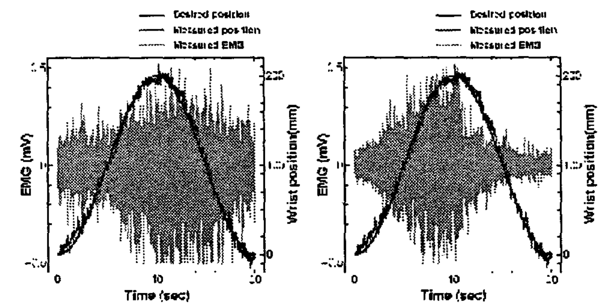
(c) with high assist

Figure 7. Experimental results with the subject A



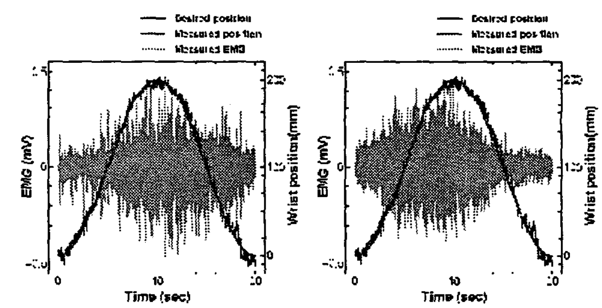
Proximal part of biceps (ch. 1) Anteror part of deltoid (ch5)

(a) without assist



Proximal part of biceps (ch. 1) Anteror part of deltoid (ch5)

(b) with low assist



Proximal part of biceps (ch. 1) Anteror part of deltoid (ch5)

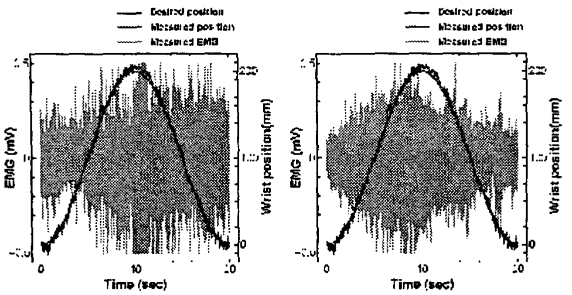
(c) with high assist

Figure 8. Experimental results with the subject B

shown in Fig. 8 and 9, respectively. From these experimental results, one can see that the activation levels of the EMG signals of the elbow and shoulder muscles were reduced when the human subject's motions were assisted by the exoskeleton. Furthermore, one can see that the activation levels of the EMG signals become lower when the assist level of the exoskeleton system is higher. The well performed target trajectory following results prove that the exoskeleton system was activated in accordance with the human subject's intention. These results show the effectiveness of the proposed exoskeleton system and its control system in human upper-limb motion assist.

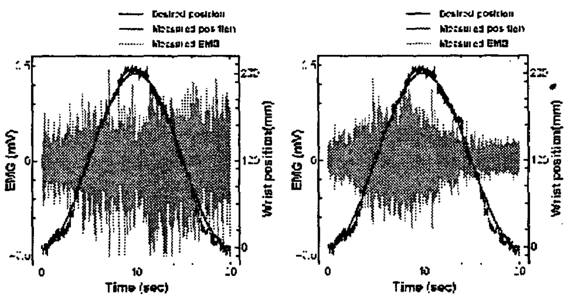
CONCLUSIONS

A 3 DOF exoskeleton system and its control system are proposed to assist the upper-limb motion of physically weak persons, such as elderly persons, handicapped persons, and injured persons, for daily activity and rehabilitation. Both elbow and shoulder joint motions of the patient were automatically assisted by the proposed exoskeleton system based on the EMG signals of the patient. The support level (the assist level) of the system can be adjusted based on his/her



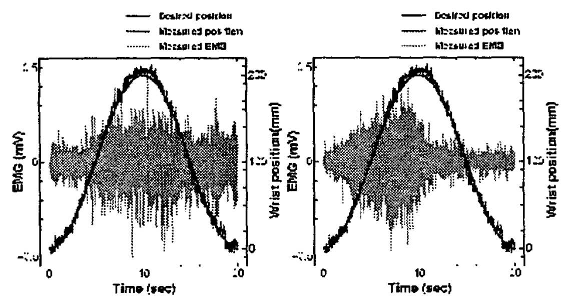
Proximal part of biceps (ch. 1) Anteror part of deltoid (ch5)

(a) without assist



Proximal part of biceps (ch. 1) Anteror part of deltoid (ch5)

(b) with low assist



Proximal part of biceps (ch. 1) Anteror part of deltoid (ch5)

(c) with high assist

Figure 9. Experimental results with the subject C

physical and physiological condition. The effectiveness of the exoskeleton and its control system was verified by experiment.

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REFERENCES

[1] V.L.Nickel, A.Karchak, Jr., and J.R.Allen: "Electrically Powered Orthotic Systems", The Journal of Bone and Joint Surgery, vol.51-A, no.2, pp.343-351, 1969.

[2] N.Benjuya and S.B.Kenney: "Hybrid Arm Orthosis", Journal of Prosthetics and Orthotics, vol.2, no.2, pp.155-163, 1990.

[3] K.Kiguchi, S.Kariya, K.Watanabe, K.Izumi, and T.Fukuda: "An Exoskeletal Robot for Human Elbow Motion Support – Sensor Fusion, Adaptation, and Control", IEEE Trans. on Systems, Man, and Cybernetics, Part B, vol.31, no.3, pp.353-361, 2001.

[4] K.Kiguchi, S.Kariya, T.Tanaka, N.Hatao, K.Watanabe, and T.Fukuda: "Intelligent Interface of an Exoskeletal Robot for Human Elbow Motion Support Considering Subject's Arm Posture", Proc. of IEEE International Conference on Fuzzy Systems, pp.1532-1537, 2002.

[5] K.Kiguchi, K.Iwami, M.Yasuda, K.Watanabe, and T.Fukuda: "An Exoskeletal Robot for Human Shoulder Joint Motion Assist", IEEE/ASME Trans. on Mechatronics, 2003. (to appear)

[6] K.A. Farry, I.D. Walker, and R.G. Baraniuk: "Myoelectric Teleoperation of a Complex Robotic Hand", IEEE Trans. on Robotics and Automation, vol.12, no.5, pp.775-788, 1996.

[7] O. Fukuda, T. Tsuji, A. Ohtsuka, and M. Kaneko: "EMG-based Human-Robot Interface for Rehabilitation Aid", Proc. of IEEE International Conf. on Robotics and Automation, pp.3942-3947, 1998.

[8] D. Nishikawa, W. Yu, H. Yokoi, and Y. Kakazu: "EMG Prosthetic Hand Controller using Real-time Learning Method", Proc. of IEEE International Conf. on Systems, Man, and Cybernetics, pp.I-153-158, 1999.

[9] D.J. Bennett, J.M. Hollerbach, Y. Xu, and I.W. Hunter: "Time-Varying Stiffness of Human Elbow Joint During Cyclic Voluntary Movement", Experimental Brain Research, vol.88, pp.433-442, 1992.

[10] R. Happee and F.C.T. Van der Helm: "The Control of Shoulder Muscles During Goal Directed Movements", An Inverse Dynamic Analysis, Journal of Biomechanics, vol.28, no.10, pp.1179-1191, 1995.

[11] B. Laursen, B.R. Jensen, G. Nemeth, and G. Sjogaad: "A Model Predicting Individual Shoulder Muscle Forces Based on Relationship Between Electromyographic and 3D External Forces in Static Position", Journal of Biomechanics, vol.31, no.8, pp.731-739, 1998.

[12] A.T.C. Au and R.F. Kirsch: "EMG-Based Prediction of Shoulder and Elbow Kinematics in Able-Bodied and Spinal Cord Injured Individuals", IEEE Trans. on Rehabilitation Engineering, vol.8, no.4, pp.471-480, 2000.