STUDY OF A 4DOF UPPER-LIMB POWER-ASSIST EXOSKELETON WITH PERCEPTION-ASSIST

Second Stage of Power-Assist

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Abstract: As a second stage of the research on power-assist exoskeleton systems, this paper presents a new concept of an upper-limb power-assist exoskeleton that can assist physically weak persons in performing their daily activities. The proposed exoskeleton assists not only the motion of the user but also the perception of the user by using sensors. In the proposed power-assist method, the assisted user's motion can be modified based on the environmental information obtained by the sensors if problems are found in the user's motion. The effectiveness of the proposed concept is evaluated by performing experiments.

1 INTRODUCTION

Decrease in birthrate and increase of percentage of aged people are progressing in several countries. In these societies, the shortage of nursing people has become a serious problem. Many robotic systems such as power-assist robots (Kiguchi, *et al.*, 2001-2007; Rosen, *et al.*, 2001; Kawamoto and Sankai, 2005; Naruse, *et al.*, 2004; Sasaki, *et al.*, 2004; Guizzo and Goldstein, 2005; Vukobratovic, 1975) have been proposed to cope with this problem. We have proposed power-assist exoskeletons to assist the upper-limb motion of physically weak persons such as disabled, injured, and/or elderly persons since the upper-limb motion is important for daily activities. The conventional exoskeletons only assist the motion of the user (Kiguchi, *et al.*, 2001-2007). As a second stage of the research on power-assist exoskeleton robot systems, this paper proposes a new concept of an upper-limb power-assist exoskeleton in order to assist physically weak persons in performing their daily activities.

In the conventional power-assist exoskeletons, the motion of the user is supposed to be assisted in accordance with the user's motion intention. The skin surface electromyogram (EMG) is often used to detect the user's motion intention (Fukuda, *et al.*, 2003) since it directly reflects the user's muscle activity. Therefore, information of the EMG signals and/or force sensors is often used to predict the user's motion intention in the conventional power-assist exoskeletons (Kiguchi, *et al.*, 2001-2007). However, in the case of physically weak persons, the perception ability is also poor sometimes. For example, such persons sometimes unknowingly trip over small obstacles because of their poor perception ability. Therefore, it is important to assist the sensing ability of physically weak persons by using sensors on robotic exoskeletons. Any sensor such as ultrasonic sensors, infrared sensors, and/or CCD sensors can be a candidate for the sensors for the perception-assist.

In the proposed power-assist method, the assisted user's motion can be modified based on the environment information obtained by the sensors if the exoskeleton detects some problems in the user's motion. For example, if the exoskeleton notices that the user's hand is going to collide with an obstacle, an additional assist force including the power-assist force is provided to the user's motion in order to avoid the collision between the user and the obstacle. On the other hand, the exoskeleton attempts to guide the user's hand to an object when the exoskeleton notices that the user is going to grasp that object, but his hand is not moving along the correct trajectory. If the modified motion by the exoskeleton is different from the user's intended motion, the exoskeleton changes its strategy in accordance with the user's motion intention. When motion modification is not required (i.e., when there is no

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problem in the user's motion), the control method is the same as the conventional EMG-based power-assist method (Kiguchi, *et al.*, 2007).

In this study, the proposed power-assist method is applied to a 4DOF upper-limb power-assist exoskeleton. The exoskeleton assists shoulder flexion/ extension, shoulder horizontal flexion/ extension, elbow flexion/ extension, and forearm supination/pronation motion.

2 UPPER-LIMB POWER-ASSIST EXOSKELETON

In order to assist 4DOF upper-limb motion, a power-assist exoskeleton (Fig. 1) was developed (Kiguchi, *et al.*, 2007). It mainly consists of a shoulder motion support part, an elbow motion support part, and a forearm motion support part. The exoskeleton system can be installed on a mobile wheel chair.

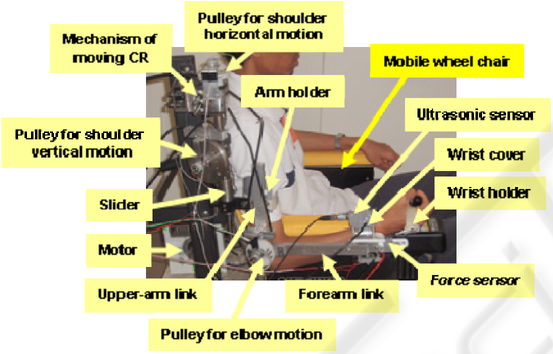
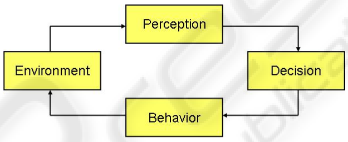


Figure 1: 4DOF upper-limb power-assist exoskeleton.

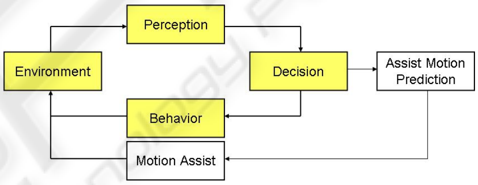
Usually, the movable range for the human shoulder is 180º in flexion, 60º in extension, 180º in abduction, 75º in adduction, 100-110º in internal rotation, and 80-90º in external rotation. The limit on the range of forearm pronation-supination motion is 50-80º in pronation and 80-90º in supination, and that on the elbow flexion-extension motion is 145º in flexion and -5º in extension. Considering the minimally required motion in everyday life and the safety of the user, the shoulder motion of the 4DOF exoskeleton is limited to 0º in extension and adduction, 90º in flexion, and 90º in abduction. The limit on its forearm motion is decided as 50º in pronation and 80º in supination, and that on the elbow motion is decided as 120º in flexion and 0º in extension.

3 POWER-ASSIST WITH PERCEPTION-ASSIST

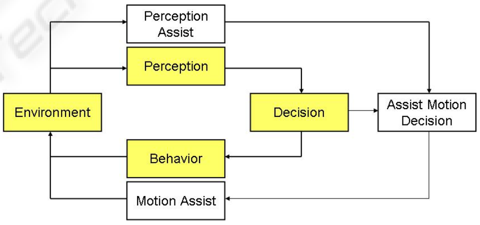
In the conventional power-assist robot systems, the user's motion intention is estimated in real-time; subsequently, the estimated motion is assisted by the power-assist robot systems (Kiguchi, *et al.*, 2001-2007). However, the perception ability is also deteriorated sometimes in the case of physically weak persons. Therefore, there is a possibility of colliding with an obstacle, tripping over a small obstacle, or failing to grasp an object even though the motion is assisted according to the user's intention. In this study, the perception of the environment is also assisted by the exoskeleton.



(a) Human behavior cycle.



(b) Conventional power-assist cycle.

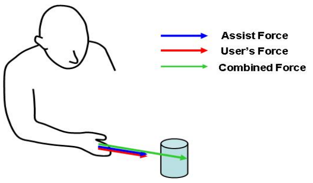


(c) Proposed power-assist cycle.

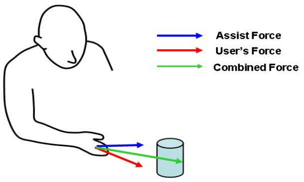
Figure 2: Power-assist cycles.

The concepts of the human behavior cycle, the conventional power-assist cycle, and the proposed power-assist cycle are depicted in Fig. 2 in order to show the difference among them.

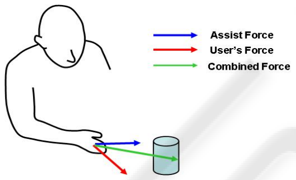
In the proposed power-assist process, when the user's motion is not interacting with the environment, the power assist is the same as the conventional power assist. Moreover, when the user interacts with the environment properly, the power-assist method continues to be the same as the conventional power-assist method (Fig. 3(a)). However, if the exoskeleton infers that the user is attempting to grab an object and the user has miscalculated the position of the object, motion modification is carried out to ensure the correct hand trajectory to the object, as shown in Fig. 3(b). If the modified motion is correct (i.e., the decision of the exoskeleton is correct), then the ordinal power assist is performed after the motion modification, as shown in Fig. 3(a). However, if the modified motion is wrong (i.e., the decision of the exoskeleton is wrong), the user attempts to reject it (sometimes unconsciously) as shown in Fig. 3(c). This rejection can automatically be detected by the exoskeleton by monitoring the user's EMG signals. Sub sequently, the exoskeleton changes its strategy, and another motion modification is carried out in order to avoid a collision with the object.



(a) Ordinal power-assist.



(b) Motion modification.



(c) Wrong motion modification.

Figure 3: Motion modification.

4 CONTROL METHOD

4.1 EMG

The EMG signals are used as the main input signals in order to control the exoskeleton in accordance with the user's motion intention. Since it is difficult to use the raw EMG signal as input information for the controller, the root mean square (RMS) value of the signal is calculated to extract the feature from the signal. The equation for the 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 for the i^{th} sampling and N is the number of samples in a segment. In this study, the number of the sample is set to be 100 and the sampling time is 500 μsec.

When a certain motion is performed, the EMG signals of the related muscles show a unique pattern. Therefore, since the magnitude of the RMS of the EMG signal indicates the activity level of the muscles, the upper-limb motion of the user can be predicted by monitoring the EMG signals of certain muscles of the user.

In order to predict the 4DOF motion, the EMG signals from the related muscles of 12 locations are measured in this study (Kiguchi, *et al.*, 2001-2007).

4.2 EMG-Based Control

The basic architecture of the controller is depicted in Fig. 4. The controller basically consists of a power-assist part and a perception-assist part. The power-assist part consists of three stages (first stage: input signal selection stage; second stage: posture region selection stage; and third stage: neuro-fuzzy control stage). This power-assist part is basically the same as the conventional EMG-based controller (Kiguchi, *et al.*, 2007). In the first stage of the power-assist part, the EMG-based control or the wrist-sensor-based control is applied in accordance to the muscle activity levels of the user. In the second stage of the power-assist part, proper neuro-fuzzy controllers are selected according to the shoulder and elbow angle regions. In the third stage of the power-assist part, the torque required for each joint motion assist is calculated by using the selected neuro-fuzzy controllers.

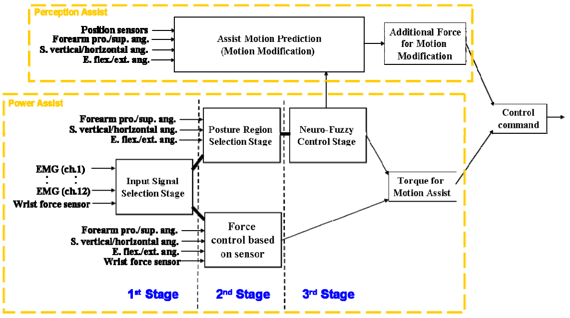


Figure 4: Controller architecture.

In the perception-assist part, the sensor information and the estimated user's motion intention (the output of the neuro-fuzzy controllers) are used to decide the motion to be modified in this part. Sensors such as ultrasonic sensors, infrared sensors, and/or CCD sensors can be used to detect the objects in the environment. In this study, an ultrasonic sensor [FW-H10R, Keyence] is applied to detect the objects.

The force vector of the assisting motion at the user's hand can be calculated on the basis of the estimated torque (the output of the neuro-fuzzy controllers) from the EMG signals in the third stage of the power-assist part. Since the estimated force vector contains noise and an estimated error, it is averaged with the estimated force vector data in the past. The relationship between the force vector at the user's hand and the joint torque vector of the user's upper-limb is written as:

$$F = J^{-T} \tau \qquad (2)$$

where F is the force vector at the user's hand (averaged by using the past data), τ is the joint torque vector of the user's upper-limb, and J is the Jacobian matrix. The estimated force vector of the user directly indicates the user's motion intention.

4.3 Perception-Assist with Ultrasonic Sensor

When a user is moving his/her arm toward an object in order to grab it, the trajectory of the hand (tip of the arm) is the almost a straight line toward the object (Flash and Hogan, 1985). Therefore, the change in the distance of the tip of arm and the reduction in the distance between the tip of arm and the object are supposed to be the same. The change in the distance of the tip of arm is calculated by using the kinematics of the exoskeleton. The reduction in the distance between the hand and the object is calculated by using the ultrasonic sensor. When the arm is moving toward the object, these two values come close to each other but vary in a particular range. This range is determined based on the experimental results. It is important to select this range to be as narrow as possible in order to identify the trajectory of the arm more accurately.

If the exoskeleton identifies that the trajectory required for the user is different from the current user's trajectory, then the exoskeleton attempts to modify the trajectory by applying an additional force at the tip of the arm. If the estimated force vector at the user's hand is changing to the modified trajectory, the exoskeleton assumes that the motion modification strategy as correct. If the user's hand is moving along the correct trajectory to grab the object, no motion modification is provided to the user's motion. However, if the estimation force vector at the user's hand is changing to a direction opposite to the motion modification direction, the exoskeleton assumes that the motion modification strategy is not correct and attempts to determine another possibility. If the exoskeleton can not determine another possibility, then it simply performs the conventional power-assist.

5 EXPERIMENT

The experimental set-up is shown in Fig. 5. As shown, a plastic bottle was used as the object. In the experiment, upper-limb motion was performed toward the object. Two interface boards (RIF–171–1 and JIF–171–1) are used to process the A/D operations of potentiometer signals, force sensor signals, EMG signals, and ultrasonic sensor signals and also to process the D/A operations required to send the calculated torque commands back to the motor drivers to control the motors. The measured EMG signals are amplified by the EMG amplifier before sending them to the interface board. The motor torque commands are calculated in the PC and then sent to the four motor drivers to operate four motors. The output of the ultrasonic sensor is sent to the RIF–171–1 interface board and then processed with the same frequency as the other signals (i.e., 2,000 Hz frequency).

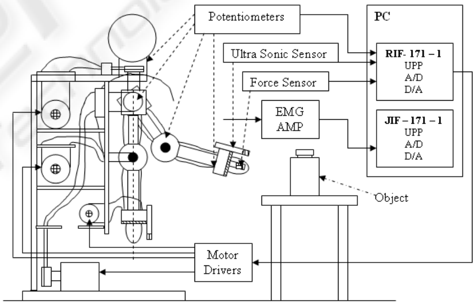
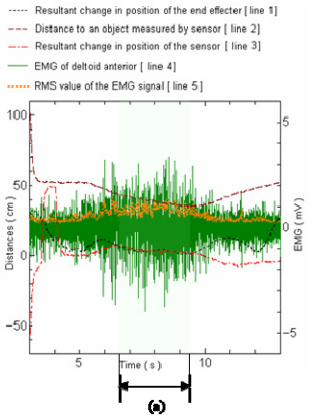


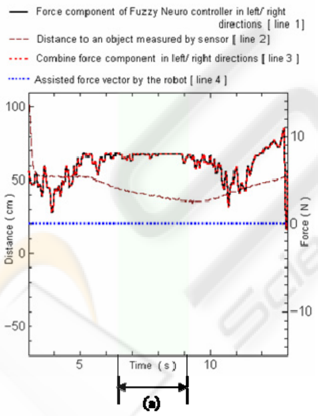
Figure 5: Experimental setup.

Three kinds of experiments were performed on the same subject in order to evaluate the effectiveness of the perception-assist. In the first experiment, the subject attempted to move the hand toward the object to grab it along the correct hand trajectory. In the second experiment, the subject also attempted to move the hand toward the object to grab it, but deliberately along a wrong trajectory. In the third experiment, the subject attempted to move the hand forward to avoid colliding with the object. In this experiment, a wrong trajectory (i.e., the trajectory for which the hand collides with the object) is generated deliberately.

Figure 6 shows the results of the first experiment. The hand trajectory determined by the exoskeleton, the distance to the object measured by the ultrasonic sensor, the change in the position of the sensor, the raw EMG signal of the deltoid – anterior part, and the RMS value are shown in Fig. 6 (a). The estimated force vector at the user's hand (calculated from the output of the neuro-fuzzy controllers), the combined force vector (modified force vector), the assisted force vector (additional force for the motion modification), and the distance to the object measured by the ultrasonic sensor are shown in Fig. 6 (b). These experimental results show that the exoskeleton effectively performs the power-assist (conventional power-assist) on the basis of the user's motion intention, when there are no problems in the user's motion.



(a) EMG signal.

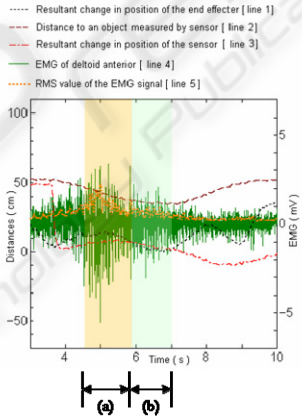


(b) Motion modification.

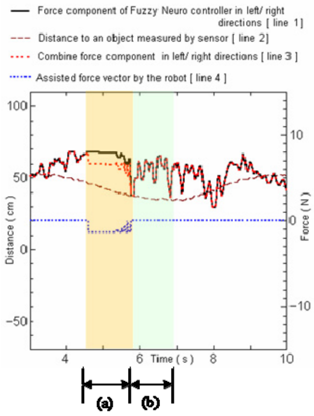
Figure 6: Experimental results of the first experiment.

Figure 7 shows the results of the second experiment. During the interval (a) in Fig. 7, the motion modification was performed to change the trajectory of the user's hand to the correct trajectory to proceed toward the object since the exoskeleton determined that the hand trajectory of the user is different from the estimated one. Since the decision of the exoskeleton was correct, the ordinal power-assist (power-assist without any motion modification) was performed until the user grasped the object (the interval (b)) after that.

Figure 8 shows the results of the third experiment. During the interval (a) in Fig. 8, the motion modification was performed to change the trajectory of the user's hand to a trajectory leading to the object since the exoskeleton determined that the trajectory of the user's hand was different from the estimated one. During the interval (b) in Fig. 8, the exoskeleton determined that its strategy was wrong and changed it to modify the trajectory of the user's hand to avoid a collision with the object. Since the second decision of the exoskeleton was correct, the ordinal power assist (power assist without any motion modification) was performed.



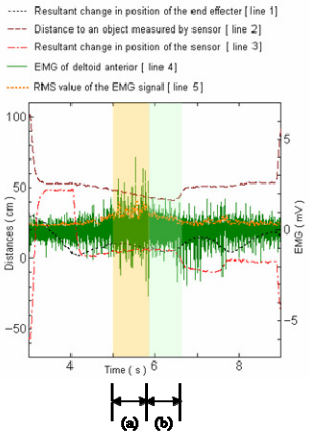
(a) EMG signal.



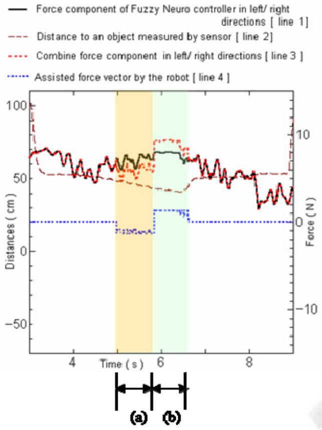
(b) Motion modification.

Figure 7: Experimental results of the second experiment.

These experimental results show the effectiveness of the proposed power-assist method with perception-assist.



(a) EMG signal.



(b) Motion modification.

Figure 8: EMG of elbow biceps (short head) with power and perception assist.

6 CONCLUSIONS

A new concept of a power-assist exoskeleton that assists not only the motion but also the perception of the user by using sensors is proposed. In the proposed power-assist method, the user motion is modified by the exoskeleton if it is necessary, although the conventional power-assist robot never modifies the user motion. The effectiveness of the proposed power-assist exoskeleton was verified by performing experiments.

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REFERENCES

Flash, T., Hogan, N., 1985. The coordination of Arm Movements: An Experimental Confirmed Mathematical Model, *Journal of Neuroscience*, vol.5, pp.1688-1703.

Fukuda, O., Tsuji, T., Kaneko, M., Otsuka , A., 2003. A Human-Assisting Manipulator Teleoperated by EMG Signals and Arm Motions, *IEEE Trans. on Robotics and Automation*, vol. 19, no. 2, pp.210-222.

Guizzo, E., Goldstein, H., 2005. The Rise of the Body Bots", *IEEE Spectrum*, vol.42, no.10, pp.42-48.

Kawamoto, H., Sankai, Y., 2005. Power Assist Method Based on Phase Sequence and Muscle Force Condition for HAL, *Advanced Robotics*, vol.19, no.7, pp.717-734.

Kiguchi, K., Esaki, R., Fukuda, T., 2005. Development of a Wearable Exoskeleton for Daily Forearm Motion Assist, *Advanced Robotics*, vol.19, no.7, pp.751-771.

Kiguchi, K., Imada, Y., Liyanage, M., 2007. EMG-Based Neuro-Fuzzy Control of a 4DOF Upper-Limb Power-Assist Exoskeleton, *Proc. of 29th Annual International Conf. of the IEEE Engineering in Medicine and Biology Society*.

Kiguchi, K., Iwami, K., Yasuda, M., Watanabe, K., Fukuda, T., 2003. An Exoskeletal Robot for Human Shoulder Joint Motion Assist, *IEEE/ASME Trans. on Mechatronics*, vol.8, no.1, pp.125-135.

Kiguchi, K., Kariya, S., Watanabe, K., Izumi, K., Fukuda, T., 2001. 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.

Kiguchi, K., Tanaka, T., Fukuda, T., 2004. Neuro-Fuzzy Control of a Robotic Exoskeleton with EMG Signals, *IEEE Trans. on Fuzzy Systems*, vol.12, no.4, pp.481-490.

Kiguchi, K., Yamaguchi, T., Sasaki, M., 2006. Development of a 4DOF Exoskeleton Robot for Upper-limb Motion Assist, *Proc. of 2006 ASME/JSME Joint Conf. on Micromechatronics for Information and Precision Equipment*, S10_03.

Naruse, K., Kawai, S., Yokoi, H., Kakazu, Y., 2004. Design of Wearable Power-Assist Device for Lower Back Support, *Journal of Robotics and Mechatronics*, vol.16, no.5, pp.489-496.

Rosen, J., Brand, M., Fuchs, M., Arcan, M., 2001. A Myosignal-Based Powered Exoskeleton System, *IEEE Trans. on System Man and Cybernetics*, part A, vol. 31, no. 3, pp. 210 - 222.

Sasaki, D., Noritsugu, T., Takaiwa, M., 2004. Development of Wearable Power-Assist Device for Lower Back Support, *Journal of Robotics and Mechatronics*, vol.16, no.5, pp.497-503.

Vukobratovic, M., 1975. *Legged Locomotion Robots and Anthropomorphic Mechanisms*, Mihailo Pupin Institute, Belgrade.