A Study on EMG-Based Control of Exoskeleton Robots for Human Lower-limb Motion Assist

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Abstract— **An exoskeleton robot is an external structural mechanism with joints and links corresponding to those of the human body. When it is worn, it transmits torques from actuators through rigid exoskeletal links to the human joints. We have been developing exoskeleton robots for assisting the motions of physically weak persons such as elderly or disabled in daily life. In this paper, we propose an electromyogram (EMG) based control (i.e., control based on the skin surface EMG signals of the user) for the exoskeleton robot to assist physically weak person's lower-limb motions. The skin surface EMG signals are mainly used as the input information for the controller. In order to generate flexible and smooth motions and take into account the changing EMG signal levels according to the physical and psychological conditions of the user, fuzzy-neuro control method has been applied for the controller. The experimental results show the effectiveness of the designed EMG-based controller for the power-assist.**

Keywords- **Exoskeleton Robot, Lower-Limb Motion, Power-Assist, Electromyogram Signals**

I. INTRODUCTION

In the recent society in which the birthrate is decreasing and the aging are progressing, it is important that physically weak persons are able to take care of themselves. We have been developing exoskeleton robots [1]-[3] for motion assist of physically weak persons such as elderly, injured and disabled. The physically weak persons are able to take care of themselves with the help of the exoskeleton robot in daily life. The lower-limb motions (hip, knee and ankle motion) are especially important for people to perform daily activities. The exoskeletons for ankle motion assist [4], knee motion assist [5], hip motion, knee motion and ankle motion assist [6]-[12] have been proposed for daily use or rehabilitation up to the present. Since around the 1950s, several exoskeleton leg systems have been studied and developed [10], and could mainly be used for two conceptually different applications [8]. 1) Walking aid for gait disorder persons or aged persons; 2) walking power augmentation to travel long distances on foot with heavy loads. Some important daily activities which involve hip and knee motions are sitting down, standing up, squatting, walking, ascending stairs and descending stairs. The electromyogram (EMG) signals are important information for robotic systems [1]-[3] to understand how the user intends to move. Therefore, the user's EMG signals are used as main input information for the controller in this study. The hip and knee forces (i.e., the generated force between the robot and the thigh of the robot user and the generated force between the robot and the lower leg of the robot user) are also used as subordinate input information for the controller.

In this paper, we design an EMG-based controller of the exoskeleton robot system for the purpose of human hip and knee motion support. Although many researches have been using EMG signals to control robots [6] [7] [12], the adaptation ability for the user's physical and physiological condition and the user's precise motion intension were not taken account. In the proposed method, the EMG signal is used as the input information for the controller, in which the user's motion intention is directly reflected. In order to make the controller adapt to the EMG signals according to the user's physical and physiological conditions, fuzzy-neuro control method has been applied. The effectiveness of the newly designed control system for the power-assist has been evaluated by experiment.

II. THE EXOSKELETON ROBOT

The exoskeleton robot should be adaptable to the human lower-limb in terms of segmental lengths and location of center of rotation. Since the exoskeleton robot is supposed to be used for daily activities of the user, it should be generated flexible and smooth motions.

The architecture of the exoskeleton robot is shown in Fig. 1. The exoskeleton robot consists of a waist holder, a thigh holder, a lower leg holder, two DC motors (Maxon DC Motors), two links, a footrest and two force sensors (hip and knee force sensor) in one leg. Locations of force sensors are shown in Fig. 2. The exoskeleton robot worn by a user is supposed to help the user's lower-limb daily motions (sitting down, standing up, squatting, ascending stairs, descending stairs and walking). There is a passive DOF (dorsiflexion/ planterflexion) in ankle joint and two active DOF (flexion/extension) in hip and knee joints. Each DC motor generates the assist torque at each joint.

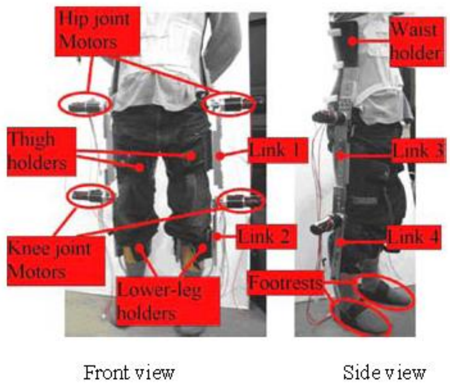


Fig. 1 Architecture of exoskeleton robot

Usually, the limitation of human knee movable range is 150 degrees in flexion and 0 degree in extension, and the limitation of human hip movable range is 110 degrees in flexion and 30 degrees in extension. Considering the practical application to everyday life and safety, the hip motion limitation of the exoskeleton robot is decided to be 110 degrees in flexion and 20 degrees in extension, and the knee motion limitation of the proposed robot is 150 degrees in flexion and 0 degree in extension. The stoppers are attached for each motion to prevent the exceeding of the movable range for safety. In addition, maximum torque of the robot is limited by the hardware and the software for safety.

Fig. 2 Location of force sensor

III. HUMAN LOWER-LIMB MOTION

Agonist-antagonist muscles exist in many human joint such as elbow, wrist, hip, knee, ankle, etc. Such human joint is usually activated by several muscles. Some of muscles are bi-articular muscles and the others are uni-articular muscles. Human hip joint generates flexion/ extension motions which are mainly actuated by the muscles of rectus femoris, tensor fasciae latae, biceps femoris, and semitendinossus [13]. Many of these muscles are bi-articular muscles that work on both of hip joint and knee joint. Human knee joint generates flexion/extension motions which are mainly actuated by the muscles of biceps femoris, semitendinossus, gastrocnemius, rectus femoris, vastus lateralis and vastus medialis. Most of these muscles are also bi-articular muscles. Human ankle joint generates dorsiflexion/plantarflexion motions which are mainly actuated by the muscles of gastrocnemius, soleus and tibialis anterior. Here, only gastrocnemius is the bi-articular muscle. The muscles activity level can be described by the EMG signal. In order to design the control system of the exoskeleton robot, the skin surface EMG signals have been analyzed in the preliminary experiments [14]. In this study, root mean square (RMS) has been applied as the feature extraction method of the EMG levels for the fuzzy-neuro controller. The equation of RMS is written as:

$$RMS = \sqrt{\frac{1}{N}\sum_{i=0}^{N} v_i^2} \tag{1}$$

where v_i is the voltage value at i^{th} sampling and N is the number of the samples in a segment. The number of the samples is set to be 100 and the sampling time is set to be 0.5ms in this study.

Eight kinds of EMG signals (ch.1: tensor fasciae latae, ch.2: rectus femoris, ch.3: vastus lateralis, ch.4: adductor longus, ch.5: gracilis, ch.6: vastus medialis, ch.7: biceps femoris – short head and ch.8: semitendinosus) are measured to control the sitting down, squatting, and standing up motions. The locations of electrodes on lower-limb muscles are shown in Fig. 3. Although bi-articular muscles such as rectus femoris and semitendinosus are activated for standing up, sitting down, squatting, ascending stairs and descending stairs motions, the motion can be classified by monitoring the activity level of the uni-articular muscles. Details can be referred in [14].

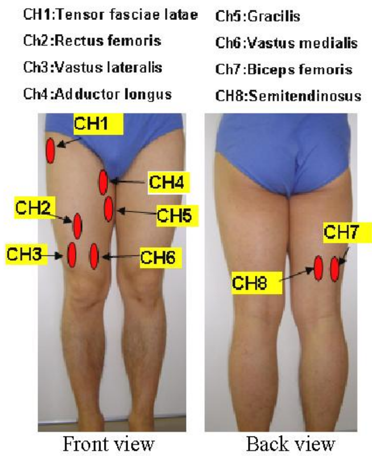


Fig. 3 Location of electrodes

IV. EMG-BASED CONTROLLER

The exoskeleton robot is controlled based on the skin surface EMG signals and the force sensor signals with the fuzzy-neuro control system [1]-[3]. In this section, a controller for the sitting down, squatting, and standing up motions of one leg is explained as an example. The same controller is used to control the other leg.

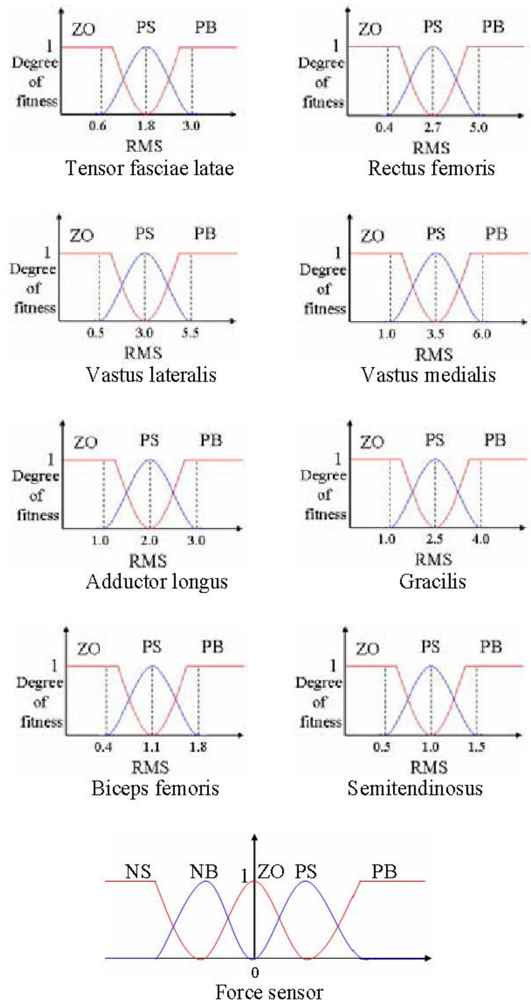


Fig. 4 Membership function for RMS of each EMG and force sensor

The initial fuzzy IF-THEN control rules of the fuzzy-neuro controller are designed based on the analyzed user's lower-limb motions in the preliminary experiment [14]. In the controller, the skin surface EMG signals and the force sensor signals are used, since the generated hip force and knee force are more reliable when the user activates the muscles little (when the EMG levels of the user are low), and the EMG signals are more reliable when the user activates the muscles actively (when the EMG levels of the user are not low). In other words, the exoskeleton robot is controlled based on the generated hip force and knee force when the EMG levels of the subject are low, and the exoskeleton robot is controlled based on the EMG signals when the EMG levels of the user are not low. Thus, the exoskeleton robot can be controlled in accordance with the user's motion intention [1]-[3]. Three kinds of fuzzy linguistic variables (ZO: zero, PS: positive small, and PB: positive big) are prepared for RMS of the each EMG and five kinds of fuzzy linguistic variables (NS: negative small, NB: negative big, ZO, PS, PB) are prepared for force sensors as shown in Fig. 4. The output of the fuzzy-neuro control system is the torque command for each motor.

The architecture of the fuzzy-neuro controller of hip and knee joint motions of one leg is depicted in Fig. 5. It consists of five layers (input layer, fuzzifier layer, rule layer, defuzzifier layer, and output layer). In order to realize the sitting down, squatting, and standing up motions, 20 fuzzy IF-THEN control rules are defined as shown in Table 1.

It is important that the controller adapts online itself to physical and physiological condition of each user. The adaptation of fuzzy-neuro controller is carried out by adjusting each weight value of the fuzzy-neuro controller to minimize the evaluation function using the back-propagation learning algorithm [1]-[3].

V. EXPERIMENT

An experiment was performed with a healthy male subject (27 years old) to show the effectiveness of the assistance of the proposed EMG-based controller. The experimental setup is shown in Fig. 6. The experimental set-up consists of two motors with encoders, a personal computer with an interface card (JIF-171-1), a motor drivers (two channels), two force sensors and power suppliers. Torque commands are sent to the motor drivers according to the output of the EMG-based controller. The rotations of the motors are measured by the encoders and fed back to the personal computer via the interface card.

In the first experiment, sitting down and standing up motions were performed as examples of daily activities under different physical conditions (normal and tired conditions) of the human subject with and without assist of the exoskeleton robot. For the experiment without assist of the robot, the force control is applied to cancel out the force between the robot and the user (not to disturb the user's motion).

The experimental results of sitting down and standing up motion under normal physical condition without and with assist of the exoskeleton robot are shown in Fig. 7 (a) and (b), respectively.

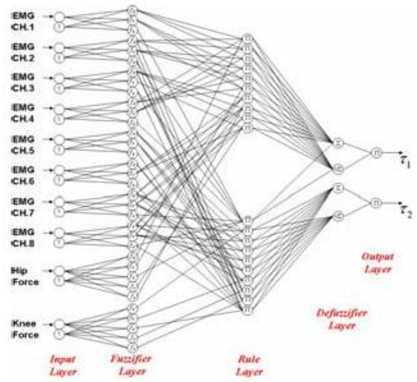


Fig. 5 Architecture of the fuzzy-neuron controller

Table 1 IF-THEN control rules

IF	*THEN*
Hip joint:	
Rule 1: ch.1 is PB and ch.2 is PB and ch.5 is PB and hip force sensor is PB	τ_1 *is 2.5*
Rule 2: ch.1 is PB and ch.2 is PB and ch.5 is PS	τ_1 *is 2.0*
Rule 3: ch.1 is PB and ch.2 is PS and ch.5 is PS	τ_1 *is 2.0*
Rule 4: ch.1 is PS and ch.2 is PS and ch.5 is PS	τ_1 *is 2.0*
Rule 5: ch.1 is PS and ch.2 is PS and ch.5 is PB	τ_1 *is 2.0*
Rule 6: ch.1 is PS and ch.2 is PB and ch.5 is PB and hip force sensor is PS	τ_1 *is 2.0*
Rule 7: ch.3 is PB and ch.10 is PB and ch.13 is PB	τ_1 *is -2.5*
Rule 8: ch.3 is PB and ch.10 is PB and ch.13 is PS and hip force is NS	τ_1 *is -2.0*
Rule 9: ch.3 is PB and ch.10 is PS and ch.13 is PS	τ_1 *is -2.0*
Rule 10: ch.3 is PB and ch.10 is PS and ch.13 is PB and hip force is NB	τ_1 *is -2.0*
Rule 11: ch.1 is ZO and ch.2 is ZO and ch.3 is ZO and ch.10 is ZO and ch.13 is ZO and hip force is ZO	τ_1 *is 0.0*
Knee joint:	
Rule 12: ch.6 is PB and ch.10 is PB and ch.13 is PB and knee force is PB	τ_2 *is 1.8*
Rule 13: ch.6 is PB and ch.10 is PB and ch.13 is PS	τ_2 *is 1.5*
Rule 14: ch.6 is PB and ch.10 is PS and ch.13 is PS	τ_2 *is 1.5*
Rule 15: ch.6 is PS and ch.10 is PS and ch.13 is PS	τ_2 *is 1.5*
Rule 16: ch.6 is PS and ch.10 is PS and ch.13 is PB	τ_2 *is 1.5*
Rule 17: ch.6 is PS and ch.10 is PB and ch.13 is PB and knee force is PS	τ_2 *is 1.5*
Rule 18: ch.2 is PB and ch.3 is PB and ch.4 is PB and knee force is NS	τ_2 *is -1.8*
Rule 19: ch.2 is PS and ch.3 is PB and ch.4 is PB and knee force is NB	τ_2 *is -1.5*
Rule 20: ch.2 is ZO and ch.3 is ZO and ch.6 is ZO and ch.4 is ZO and ch.10 is ZO and ch.13 is ZO and knee force is ZO	τ_2 *is 0.0*

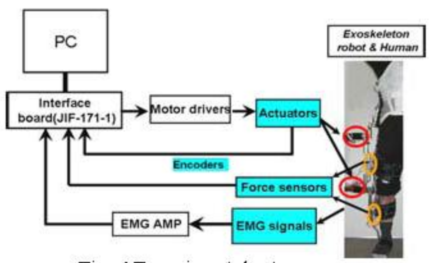
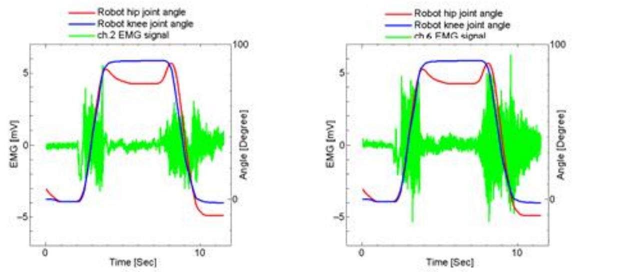


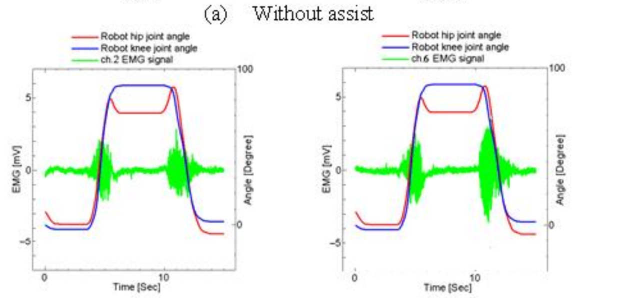
Fig. 6 Experimental setup

The experimental results of sitting down and standing up motion under tired physical condition without and with assist of the exoskeleton robot are shown in Fig. 8 (a) and (b), respectively. Only the results of EMG signals of ch.2 (rectus femoris) and ch.6 (vastus medialis), which represent the hip and knee muscles are shown. These results show that the activity levels of the muscles were reduced when the motions were assisted by the exoskeleton robot. Furthermore, one can see that the robots hip and knee angles were smoothly controlled.



Ch.2 Ch.6

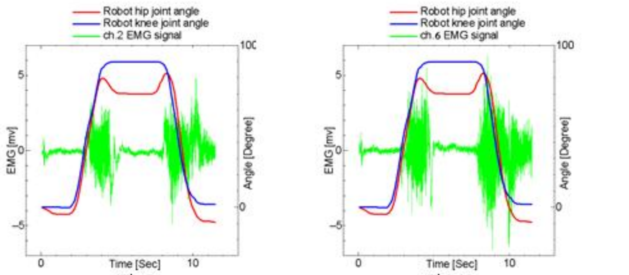
(a) Without assist



Ch.2 Ch.6

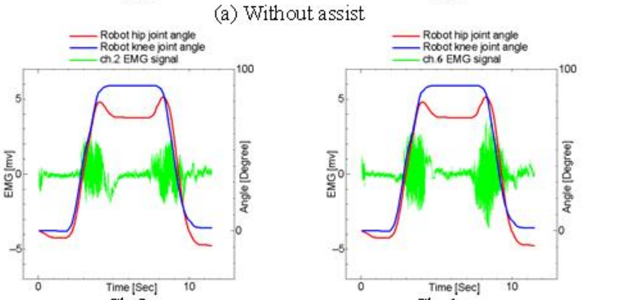
(b) With assist

Fig. 7 Results of the motions of normal physical condition



Ch.2 Ch.6

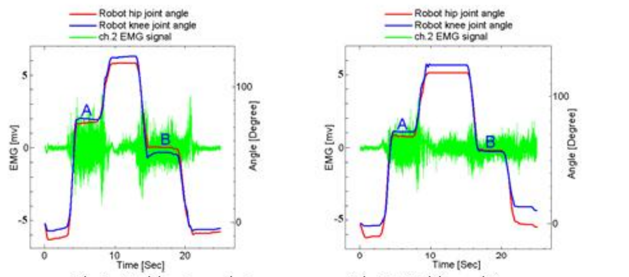
(a) Without assist



Ch.2 Ch.6

(b) With assist

Fig. 8 Results of the motions of tired physical condition



Ch.2. Without assist Ch.2. With assist

Fig. 9 Results of the stopping in arbitrary position

In the second experiment, the squatting motion and the standing up motion is stopped for a while during the motion to show that the robot is controlled under the motion intention of the user. Fig. 9 shows the results of the second experiment with and without assist of the robot. Here, only the result of EMG signal of ch.2 is presented as an example. Region A and region B show the stopped positions. These results show that the activity levels of the muscles were reduced when the motions were assisted by the exoskeleton robot. Furthermore, one can see that the robots hip and knee angles were also smoothly controlled.

VI. Conclusion

An EMG-based controller is designed to control an exoskeleton robot for assisting physically weak person's lower-limb motion. The effectiveness of the proposed EMG-based controller for the power-assist of the lower-limb motion was verified by experiment with a healthy human subject.

Acknowledgment

This work was supported by Japan Society of Promotion of Science (JSPS) Grant-in-Aid for Scientific Research (C) 19560258.

References

[1] K. Kiguchi, T. Tanakda, T. Fukuda, "Neuro-fuzzy control of a robotic exoskeleton with EMG signals," IEEE Trans. on Fuzzy Systems, vol.12, no.4, pp.481-490, 2004.

[2] K. Kiguchi, R. Esaki, T. Fukuda, "Development of a wearable exoskeleton for daily forearm motion assist", Advanced Robotics, vol.19, no.7, pp.751-771, 2005.

[3] K. Kiguchi, "Active Exoskeletons for Upper-Limb Motion Assist", Journal of Humanoid Robotics, 2007. (to appear)

[4] S.K.Au, P. Dilworth, H. Herr, "An Ankle-Foot Emulation System for the Study of Human Walking Biomechanics", Proc. of IEEE International Con. on Robotics and Automation, pp.2939-2945, 2006

[5] J.E.Pratt, B.T.krupp, C.J.Morse, "The RoboKnee: An Exoskeleton for Enhancing Strength and Endurance During Walking", Proc. of IEEE International Con. on Robotics and Automation, pp.2430-2435, 2004

[6] S.Lee, Y. Sankai, "Virtual impedance adjustment in unconstrained motion for an exoskeleton robot assisting the lower limb", Advanced Robotics, Vol.19, No.7, pp773-795, 2005.

[7] H. Kawamoto, Y. Sankai, "Power assist method based on Phase Sequence and muscle force condition for HAL", Advanced Robotics, Vol.19, No.7, pp773-795 (2005) VSP and Robotics Society of Japan 2005.

[8] Y.CanJun, N.Bin, C.Ying, "Adaptive Neuro-Fuzzy Control Based Development of a Wearable Exoskeleton Leg for Human Walking Power Augmentation", Proc. of the 2005 IEEE/ASME Intl. Conference on Advanced Intelligent Mechatronics Monterey, California, USA, 24-28 July,pp467-472, 2005.

[9] N. Hata, Y. Hori, "Realization of Robotic-Suit for Walking Assistance", SICE Annual Conference in Sapporo, Hokkaido, Japan, August 4-6, pp2266-2271, 2004.

[10] http://gatel.fzi.de/ids/public_html/historical.php

[11] G.Cheron, F. Leurs, A.Bengoetxea, J.P.Draye, M.Destree, B.Dan, "A dynamic recurrent neural network for multiple muscles electromyographic mapping to elevation angles of the lower limb in human locomotion", Journal of Neuroscience Methods, vol.129, pp.95-104, 2003.

[12] G.S.Sawicki, K.E.Gordon, D.P.Ferris, "Powered Lower Limb Orthoses: Application in Motor Adaptation and Rehabilitation", Proc. of the 2005 IEEE 9th International Conference on Rehabilitation Robotics, Chicago, IL, USA, June 28-July 1, pp206-211 2005.

[13] F.H.Martini, M.J.Timmons, and R.B.Tallitsch, *Human Anatomy*, Pearson Education, Inc., New Jersey, pp.305-321, 1997.

[14] H.He, K.Kiguchi "A Study on Lower-Limb Muscle Activities during Daily Lower-Limb Motions" Proc. of The International Special Topic Conference on Information Technology Applications in Biomedicine 2007.(to appear)