2011 IEEE International Conference on Rehabilitation Robotics
Rehab Week Zurich, ETH Zurich Science City, Switzerland, June 29 - July 1, 2011

An Upper-Limb Power-Assist Robot with Tremor Suppression Control

Kazuo Kiguchi
Dept. Advanced Technology Fusion,
Saga University, Saga, Japan
kiguchi@ieee.org

Yoshiaki Hayashi
Dept. Advanced Technology Fusion,
Saga University, Saga, Japan
hayashi@me.saga-u.ac.jp

Toyoko Asami
Rehabilitation Center,
Saga University Hospital, Saga, Japan
asamit@cc.saga-u.ac.jp

***Abstract*—A tremor is somewhat rhythmic motion that may occur in various body parts. An essential tremor is one of the most common tremor disorders of the arm and it may occur during a voluntary motion. If the essential tremor occurs in the arm, the person may not be able to achieve the target task properly since the human performs various sensitive tasks with certain tools. Suppressing the vibration of the grasped tool is important when the person uses the tool. Power-assist robots are useful for not only the physically weak persons but also for persons involved in physically-taxing work such as a care or a farm work. Although some power-assist robots are controlled by using electromyogram (EMG) signals, EMG signals are influenced by the essential tremor. Therefore, when the user who suffers from the tremor uses the power-assist robot controlled based on EMG signals, the robot might assist the vibration of the tremor. In this paper, the tremor suppression control method is proposed for upper-limb power-assist robot. In proposed method, the vibrations of the hand and the tip of the tool are suppressed. The validity of the proposed method was verified by the experiments.**

Keywords- tremor suppression, power-assist robot.

I. INTRODUCTION

A human motion is classified into two groups. One is a voluntary motion and the other is an involuntary motion. In a power-assist robot which is activated based on electromyogram (EMG) signals, the EMG signals are used to estimate the user's motion intention in real-time. Since the EMG signal is generated according to the muscle activity level, the EMG signal is generated not only when a voluntary motion occurs but also when an involuntary motion occurs. Therefore, the involuntary motion might be misunderstood as the user's motion intention in the EMG-based power-assist robot.

A tremor is one of the involuntary motions. It is somewhat rhythmic motion that may occur in various body parts such as an arm, a leg and so on. An essential tremor is the most common tremor disorder of the arm and it may occur during a voluntary motion such as writing [4, 5]. If the essential tremor occurs in the arm, the person may not be able to achieve the target task properly because the human performs various sensitive tasks with certain tools. To suppress a tremor, many methods have been proposed [1-3]. However, in the case of the arm or the hand, most of these methods are focused on the hand position. Although it is true that suppressing a tremor at the hand is very important, suppressing the vibration of the grasped tool is important as well as that of the hand when the person uses the tool.

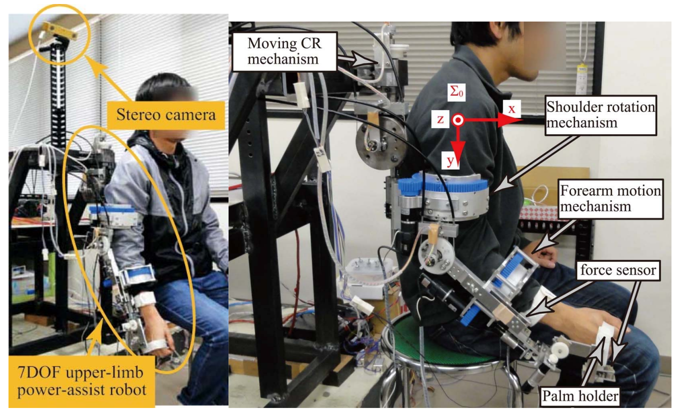

Fig. 1 7DOF upper-limb power-assist exoskeleton robot with stereo

In this paper, the tremor suppression control method for upper-limb power-assist robot is proposed. In the proposed method, the vibrations of the hand and the tip of the tool are suppressed. The validity of the proposed method was verified by the experiments.

II. UPPER-LIMB POWER-ASSIST EXOSKELETON ROBOT

The 7DOF upper-limb power-assist exoskeleton robot [6] used in this study is shown in Fig. 1. The robot contains seven DC motors with encoders or potentiometers to measure each joint angle. In addition, force/torque sensors are set in forearm and wrist part to measure the force between the user and the robot. The robot can assist the most of upper-limb motions (shoulder vertical and horizontal flexion/extension motion, shoulder internal/external rotation motion, elbow flexion/extension motion, forearm supination/pronation motion, wrist palm flexion/extension motion and wrist palm radial/ulnar deviation motion). The stereo camera is installed to rearward of the robot as shown in Fig. 1. This camera is used to recognize the interaction between the user and the environment. Furthermore, the shape of the grasping tool is recognized by the camera when user uses a tool.

III. EMG-BASED CONTROL METHOD

To estimate the user's intention and control the 7DOF upper-limb power-assist exoskeleton robot, sixteen channels of EMG signals are used as main input signals. The locations of EMG electrodes are shown in Fig. 2 and each channel mainly corresponds to one muscle as shown in Table 1.

In order to extract the features of the raw EMG signal, the root mean square (RMS) of EMG signal is calculated and used as an input for the controller. RMS calculation is calculated as follows:

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

where N is the number of the segments (N=400), v_i is the voltage at i^{th} sampling. The sampling frequency is 1.5 kHz. Using sixteen RMS values, the joint torque vector is written as:

$$\boldsymbol{\tau} = \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \\ \tau_5 \\ \tau_6 \\ \tau_7 \end{bmatrix} = \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{115} & w_{116} \\ w_{21} & w_{22} & \cdots & w_{215} & w_{216} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ w_{61} & w_{62} & \cdots & w_{615} & w_{616} \\ w_{71} & w_{72} & \cdots & w_{715} & w_{716} \end{bmatrix} \begin{bmatrix} ch_1 \\ ch_2 \\ \vdots \\ ch_{15} \\ ch_{16} \end{bmatrix} \tag{2}$$

where $\boldsymbol{\tau}$ is the joint torque vector, τ_i are the joint torques for i^{th} joint motor, w_{ij} is the weight value for j^{th} EMG signal to estimate the torque of motor-i, and ch_j represents the RMS value of the EMG signal measured in channel i. The weight matrix (i.e., the muscle-model matrix) in eq. (2) can be defined using the knowledge of human upper-limb anatomy or the results of experiments. Therefore, the joint torque vector generated by muscle force can be calculated if every weight for the EMG signals is properly defined. Furthermore, the posture of the upper-limb affects the relationship between the EMG signals and the generated joint torques because of anatomical reasons such as change of the moment arm. In other words, the role of each muscle for a certain motion varies in accordance with joint angles. Consequently, the effect of the posture difference of the upper-limb must be taken into account to estimate the correct upper-limb motion for the power-assist. Therefore, a neuro-fuzzy muscle-model matrix modifier [6, 8] is applied to take into account the effect of the upper-limb posture change of the user in on-line manner. The neuro-fuzzy modifier is used to adjust the weight matrix in eq. (2) by multiplying the coefficients in accordance with the upper-limb posture of the user, so that the effect of upper-limb posture difference can be compensated effectively.

To estimate user's motion intention, hand force vector is calculated based on the estimated joint torque vector. $\boldsymbol{\tau}$ is transferred to the hand force vector of the user as follows:

$$\boldsymbol{F}_{end} = \boldsymbol{J}^{-T}\boldsymbol{\tau} \tag{3}$$

$$\boldsymbol{F}_{avg} = \frac{1}{N_f}\sum_{i=1}^{N_f} \boldsymbol{F}_{end}(i) \tag{4}$$

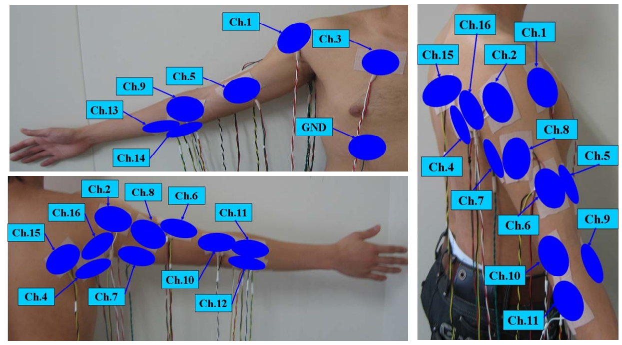

Fig. 2 7DOF upper-limb power-assist exoskeleton robot.

Table 1 Muscles for each EMG channel

EMG CHANNEL	MUSCLE
Ch.1	Deltoid-anterior
Ch.2	Deltoid-posterior
Ch.3	Pectoralis major-clavicular
Ch.4	Teres major
Ch.5	Biceps-short head
Ch.6	Biceps-long head
Ch.7	Triceps-long head
Ch.8	Triceps-lateral head
Ch.9	Pronator teres
Ch.10	Supinator
Ch.11	Extensor carpi radialis brevis
Ch.12	Extensor carpi ulnaris
Ch.13	Flexor carpi radialis
Ch.14	Flexor carpi ulnaris
Ch.15	Infraspinatus
Ch.16	Teres minor

where $\boldsymbol{F}_{end}$ is the hand force vector, $\boldsymbol{J}$ is the Jacobian matrix, $\boldsymbol{F}_{avg}$ is average of $\boldsymbol{F}_{end}$ in N_f number of samples. Then, the hand acceleration vector can be calculated based on eq. (4).

$$\ddot{\boldsymbol{X}}_d = \boldsymbol{M}^{-1}\boldsymbol{F}_{avg} \tag{5}$$

where $\ddot{\boldsymbol{X}}_d$ is the desired hand acceleration vector, and $\boldsymbol{M}$ is the weight matrix of the user's upper-limb and the robot. The desired hand velocity and position can be calculated based on eq. (5). In addition, the following impedance control equation is used to calculate the resultant hand force vector $\boldsymbol{F}$.

$$\boldsymbol{F} = \boldsymbol{M}\ddot{\boldsymbol{X}}_d + \boldsymbol{B}\left(\dot{\boldsymbol{X}}_d - \dot{\boldsymbol{X}}\right) + \boldsymbol{K}\left(\boldsymbol{X}_d - \boldsymbol{X}\right) \tag{6}$$

where $\boldsymbol{B}$ is the viscous coefficient matrix and $\boldsymbol{K}$ is the spring coefficient matrix. The impedance parameters $\boldsymbol{B}$ and $\boldsymbol{K}$ in eq. (6) depend on the upper-limb posture and activity levels of activated upper-limb antagonist muscles. Therefore, the impedance parameters have to be adjusted in real time. So $\boldsymbol{B}$ and $\boldsymbol{K}$ are defined based on the upper-limb posture and activity levels of activated upper-limb antagonist muscles [9].

Finally, the joint torque command vector $\boldsymbol{\tau}_{motor}$ is calculated as follows:

$$\boldsymbol{\tau}_{motor} = \kappa \boldsymbol{J}^{\mathrm{T}}\boldsymbol{F} \tag{7}$$

where κ is the power-assist rate.

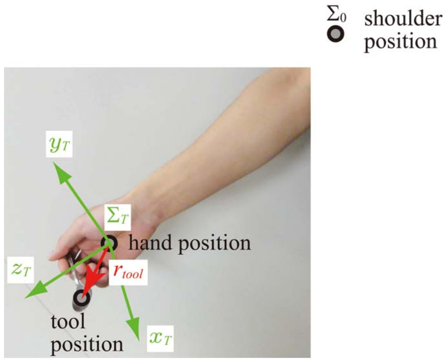

Fig. 3 Coordinate frames.

When the user's muscle activation levels are low, force/torque sensor-based control is used to control the robot [6, 7].

IV. TREMOR SUPPRESSION CONTROL

When the essential tremor occurs, the estimated hand force vector $\boldsymbol{F}_{avg}$ includes the involuntary motion caused by the essential tremor. In the tremor suppression control, this influence of the essential tremor is reduced at hand and tool positions.

First, the influence of the essential tremor is reduced at hand position. Because $\boldsymbol{F}_{avg}$ includes the involuntary motion caused by the essential tremor, $\boldsymbol{X}_d$ in eq. (6) includes the influence of the essential tremor too.

Since the essential tremor is rhythmic motion and its frequency is 6-12Hz, the vibrational component of $\boldsymbol{X}_d$ is extracted by using the band pass filter (BPF) in the controller. In addition, the component of the user's intention of $\boldsymbol{X}_d$ is extracted by using the low pass filter (LPF). Here, $\boldsymbol{X}_{tre}$ represents the vibrational component of $\boldsymbol{X}_d$ and $\boldsymbol{X}_{usr}$ represents the component of the user's intention of $\boldsymbol{X}_d$. The vibration of tremor is suppressed by using the opposite phase vector of $\boldsymbol{X}_{tre}$. The controller treats the sum of $\boldsymbol{X}_{usr}$ and the opposite phase vector of $\boldsymbol{X}_{tre}$ as the desired hand position vector instead of $\boldsymbol{X}_d$ in eq. (4) as follows.

$$\boldsymbol{X}_{avg} = \boldsymbol{X}_{usr} - \boldsymbol{X}_{tre} \tag{8}$$

Next, the influence of the essential tremor is reduced at tool position. In this paper, the tool position means the position of the center of gravity (COG) which is recognized and calculated by using stereo camera. In this case, the position of the COG is calculated based on assumption that the density is the same at any points of the grasping tool because the camera cannot measure its mass. $\boldsymbol{r}_{tool}$ is the vector from the hand position to the tool position and Σ_0 and Σ_T are the coordinate frames as shown in Fig. 3. We assume that ${}^T\boldsymbol{r}_{tool}$ does not change by the essential tremor. Then, ${}^T\boldsymbol{r}_{tool}$ can be calculated from the hand position and the tool position because the hand position can be calculated by the encoders and potentiometers of each joint. This means the vibration of the tool can be measured. The vibrational component of ${}^T\boldsymbol{r}_{tool}$ is extracted by using the BPF as well as $\boldsymbol{F}_{avg}$. ${}^T\boldsymbol{r}_v$ represents this vibrational component. In order to suppress ${}^T\boldsymbol{r}_v$, following equation is calculated.

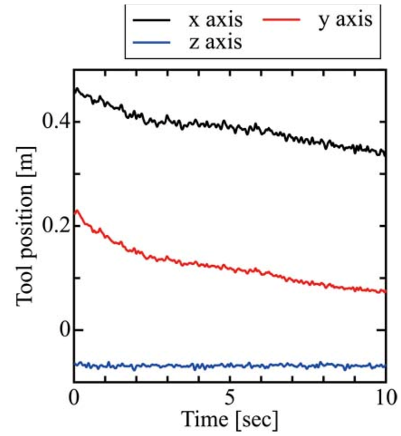

Fig. 4 Tool position when power-assist torque is calculated using (7).

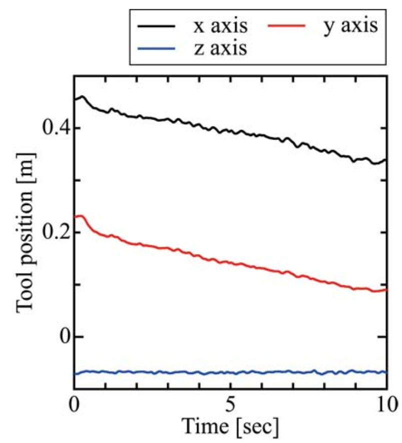

Fig. 5 Tool position when power-assist torque is calculated the proposed method.

$${}^T\boldsymbol{F}_v = -\boldsymbol{B}_v\,{}^T\dot{\boldsymbol{r}}_v - \boldsymbol{K}_v\,{}^T\boldsymbol{r}_v \tag{9}$$

where B_v and K_v are the viscous coefficient matrix and the spring coefficient matrix, respectively. Equation (9) is the impedance control equation when the desired values are zero.

As a result, the final joint torque command vector $\boldsymbol{\tau}_{final}$ can be written as follows:

$$\boldsymbol{\tau}_{final} = \boldsymbol{\tau}_{motor} + \boldsymbol{J}_v^{\mathrm{T}} \boldsymbol{R}^T \boldsymbol{F}_v \tag{10}$$

where $J_v \in \Re^{3\times7}$ is the jacobian matrix. $\boldsymbol{R} \in \Re^{3\times3}$ is the rotation matrix from Σ_t to Σ_0.

V. EXPERIMENTS

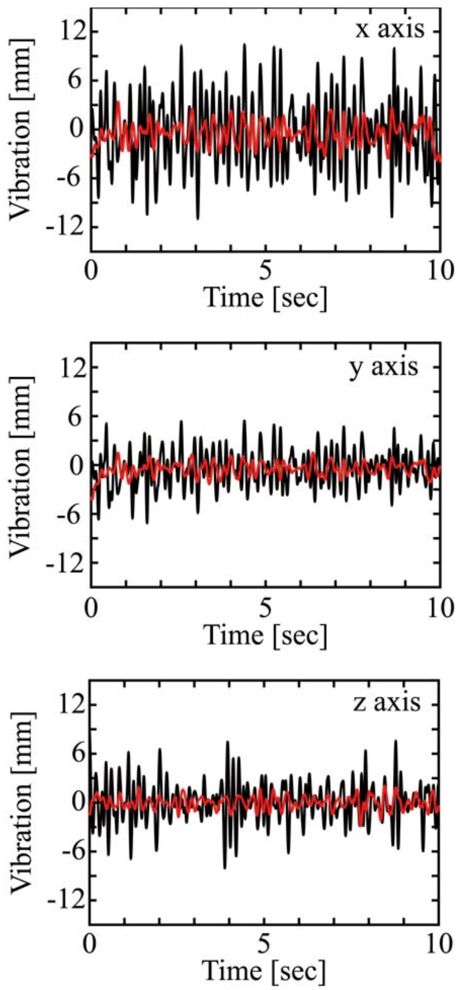

Fig. 6 The vibrational component of the tool position.

To investigate the effects of the method, the experiments have been carried out. In the experiments, a subject carries a spoon to mouth with the torque calculated using the proposed method and with the torque calculated using eq. (7). The subject is a young healthy male. The subject generates a vibration with the same frequency of the essential tremor on purpose because the subject is a health person. The experimental results are shown in Figs. 4-6.

Figure 4 shows the tool position when power-assist torque is calculated using eq. (7). The black, red and blue lines are the tool positions of x axis, y axis and z axis, respectively. On the other hand, Fig. 5 shows the tool position when power-assist torque is calculated by the proposed method. The tool position with the proposed method is smoother than that without the method compared with the results shown in Figs. 4-5.

Figure 6 shows the vibrational component of the spoon position. The black line is the vibration without the proposed method and the red line is the vibration with the proposed method, respectively. From Fig. 6, the vibration of the spoon when power-assist torque is calculated by the proposed method becomes smaller than one when power-assist torque is calculated using eq. (7). From the experimental results, the sums of the amplitude of vibration for each axis are shown in Table 2. The proposed method can reduce the vibration of the spoon by about 60%.

Table 2 The sum of the amplitude of vibration

	x axis [m]	y axis [m]	z axis [m]
Without the method	21.4	11.5	11.3
With the method	7.37	4.65	3.96

It is thought that the proposed method can be used to reduce the vibration of another involuntary motion by changing a frequency range of BPF according to a user.

VI. CONCLUSIONS

When the user who suffers from the tremor uses the power-assist robot controlled based on EMG signals, the robot might assist the vibration of the tremor also, because EMG signals are influenced by the essential tremor. In order to suppress the influence of the essential tremor for an upper-limb power-assist robot, the tremor suppression control method is proposed. In the proposed method, the hand position and the tool position are focused and each vibration component is extracted. The extracted vibration component is used to suppress the vibration. The validity of the proposed method was verified by the experiments. In the future work, we will verify the effectiveness of the proposed method by performing the experiments with persons who suffer from the essential tremor disorder.

REFERENCES

[1] F. Widjaja, C. Y. Shee, P. Poignet, and W. T. Ang, “Filtering Intended Motion for Real-time Tremor Compensation in Human Upper Limb using Surface Electromyography,” 31th Annual Inter. Conf. of the IEEE EMBS, pp. 2996–2999, 2009.

[2] K. Yano, E. Ohara, S. Horihata, T. Aoki, and Y. Nishimoto, “Development of Tremor Suppression Control System Using Adaptive Filter and Its Application to Meal-assist Robot,” Trans. of the Society of Instrument and Control Engineers, Vol. 45, No. 12, pp. 638–645, 2009.

[3] S. Pledgie, K.E. Barner, S.K. Agrawal, and T. Rahman, “Tremor Suppression Through Impedance Control,” IEEE Trans. of Rehabilitation Engineering, Vol. 8, No. 1, pp. 53–59, 2000.

[4] S. Pledgie, K. E. Barner, S. K. Agrawal, and T. Rahman, “Observations on essential (heredofamilial) tremor,” Brain, Vol. 72, No. 2, pp. 113-139, 1949.

[5] E. D. Louis, B. Ford, and L. F. Barnes, “Clinical subtypes of essential tremor,” Arch Neurol, Vol. 57, pp. 1194-1198, 2000.

[6] R.A.R.C. Gopura and K. Kiguchi, “SUEFUL-7: A 7DOF Upper-Limb Exoskeleton Robot with Muscle-Model-Oriented EMG-Based Control”, Proc. of IEEE/RSJ International Conf. on Intelligent Robots and Systems, pp.1126-1131, 2009.

[7] K. Kiguchi, T. Tanaka and 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.

[8] K. Kiguchi and Q. Quan, “Muscle-Model-Oriented EMG-Based Control of an Upper-Limb Power-Assist Exoskeleton with a Neuro-Fuzzy Adjuster”, Proc. of IEEE World Congress of Computational Intelligence, pp.1179-1184, 2008.

[9] K. Kiguchi, R.A.R.C. Gopura, Y. Hayashi, and Y. Li, “The Effect of Impedance Parameters in 7DOF Upper-Limb Power-Assist Exoskeleton Robot”, Proc. of The First IFToMM Asian Conference on Mechanism and Machine Science, No.250139, 2010.