35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Upper-Limb Tremor Suppression with a 7DOF Exoskeleton Power-Assist Robot*

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Abstract— **A tremor which is one of the involuntary motions is somewhat rhythmic motion that may occur in various body parts. Although there are several kinds of the tremor, an essential tremor is the most common tremor disorder of the arm. The essential tremor is a disorder of unknown cause, and it is common in the elderly. The essential tremor interferes with a patient's daily living activity, because it may occur during a voluntary motion. If a patient of an essential tremor uses an EMG-based controlled power-assist robot, the robot might misunderstand the user's motion intention because of the effect of the essential tremor. In that case, upper-limb power-assist robots must carry out tremor suppression as well as power-assist, since a person performs various precise tasks with certain tools by the upper-limb in daily living. Therefore, it is important to suppress the tremor at the hand and grasped tool. However, in the case of the tremor suppression control method which suppressed the vibrations of the hand and the tip of the tool, vibration of other part such as elbow might occur. In this paper, the tremor suppression control method for upper-limb power-assist robot is proposed. In the proposed method, the vibration of the elbow is suppressed in addition to the hand and the tip of the tool. The validity of the proposed method was verified by the experiments.**

I. INTRODUCTION

Power-assist robots are useful for the elderly or physical weak persons to help their independent lives. An electromyogram (EMG) signal is one of the commonly used input signals to control power-assist robots because the EMG signals are generated when muscles are activated [1-3]. In order to assist a user's activities, EMG-based power-assist robots are supposed to estimate the user's motion intention based on the measured EMG signals. However, in some cases, measured EMG signals might contain other components of unintentional motions of a user because a human motion is classified into two groups: a voluntary motion and an involuntary motion. An involuntary motion is an irrational motion which occurs regardless of human motion intention. Since the muscles are also activated for the involuntary motion, EMG signals are affected by the involuntary motion. Therefore, power-assist robots might misunderstand the user's motion intention, when the involuntary motion occurs during the power-assist.

A tremor which is one of the involuntary motions is somewhat rhythmic motion that may occur in various body parts such as an arm, a leg and so on. The tremor is grouped into several categories according to amplitude and frequency of vibration. In the categories of the tremor, an essential tremor is the most common tremor disorder of the arm. The essential tremor is a disorder of unknown cause, and it is common in the elderly. The essential tremor interferes with a patient's daily living activity such as writing a letter or drinking water with a glass, because it may occur during a voluntary motion [4,5]. If a patient of the essential tremor uses an EMG-based power-assist robot, the vibration of a tremor might become larger by incorrect assist of the robot. Therefore, upper-limb power-assist robots must carry out tremor suppression, since a person performs various precise tasks with certain tools by the upper-limb.

Many tremor estimation methods [6] and tremor suppression methods [7-10] have been proposed up to the present. In the case of upper-limb, it is important that suppressing a tremor at the hand, and most of these methods focused on the hand position. However, suppressing the vibration of the grasped tool is also important because a person uses various tools by a hand. For the upper-limb power-assist robot, the tremor suppression control method which suppressed the vibrations of the hand and the tip of the tool has been proposed [11]. However, in this method, vibration of other part such as elbow might occur.

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

II. UPPER-LIMB POWER-ASSIST EXOSKELETON ROBOT

Figure 1 shows the 7DOF upper-limb power-assist exoskeleton robot [3] used in this study. The robot can assist seven 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). To recognize the interaction between the user and the environment, a stereo camera is installed to rearward of the robot. If a user uses a tool, the robot recognizes the shape of the grasping tool [11].

The robot is controlled based on EMG signals of the user. To estimate the user's motion intention, sixteen channels of EMG signals are measured as shown in Table I. The root mean square (RMS) values are calculated from measured EMG signals in order to extract the feature of EMG signals. Each joint torque of upper-limb is estimated from the sum of the

*Resrach supported by Japan Society of Promotion of Science (JSPS) Grant-in-Aid for Scientific Research (C) 23560293.

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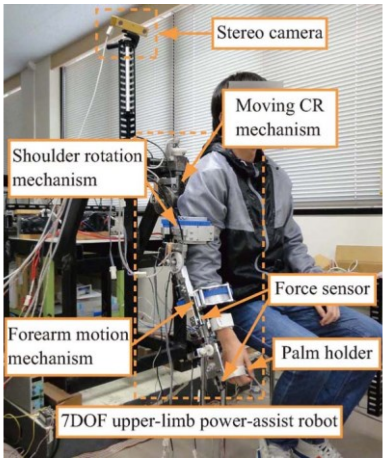

Fig. 1 7DOF upper-limb power-assist exoskeleton robot with stereo.

Table I Muscles for each EMG channel

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

values of the product of RMS values and weight values. Since the amount of the EMG signal is different between persons, and changes depending on the posture of upper-limb, the weight values must be modified. In order to take into account the change of EMG signals, each weight value is modified by the neuro-fuzzy modifier in on-line manner [14]. After estimation of each joint torque, the hand force vector is calculated as follows.

$$\boldsymbol{F}_{end} = \boldsymbol{J}^{-\mathrm{T}} \boldsymbol{\tau} \tag{1}$$

$$\boldsymbol{F}_{avg} = \frac{1}{N_f} \sum_{i=1}^{N_f} \boldsymbol{F}_{end}(i) \tag{2}$$

where $\boldsymbol{F}_{end}$ is the hand force vector, $\boldsymbol{J}$ is the Jacobian matrix, $\boldsymbol{\tau}$ is the joint torque vector, $\boldsymbol{F}_{avg}$ is the average of $\boldsymbol{F}_{end}$, and N_f is the number of samples. The desired hand acceleration vector is calculated based on eq. (2). Then, the resultant force vector is obtained by applying the impedance control method.

$$\boldsymbol{F} = \boldsymbol{M}\ddot{\boldsymbol{X}}_d + \boldsymbol{B}(\dot{\boldsymbol{X}}_d - \dot{\boldsymbol{X}}) + \boldsymbol{K}(\boldsymbol{X}_d - \boldsymbol{X}) \tag{3}$$

where $\boldsymbol{F}$ is the resultant force vector. $\boldsymbol{M}$, $\boldsymbol{B}$, and $\boldsymbol{K}$ are the weight matrix, the viscous coefficient matrix, and the spring coefficient matrix, respectively. $\boldsymbol{X}_d$ is the desired hand position and orientation. Finally, each joint torque (i.e., each motor output) is calculated based on the resultant force vector with the Jacobian matrix. The power-assist rate (constant value) is used to define how much assist the robot performs for the user.

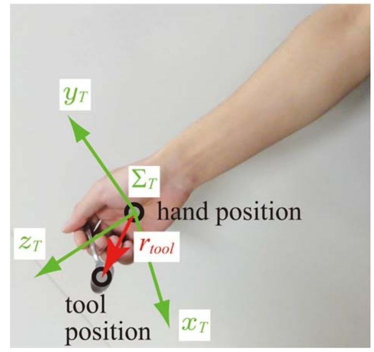

Fig. 2 Coordinate frames at hand.

III. Tremor Suppression Control

If the essential tremor occurs during the operation of the power-assist robot, the estimated hand force vector $\boldsymbol{F}_{end}$ and $\boldsymbol{F}_{avg}$ might be affected by the essential tremor. In the proposed method, the influence of the essential tremor is reduced at elbow position in addition to hand and tool positions.

A. Suppression control at hand and tool positions

The essential tremor is a rhythmic motion and its frequency is 6-12Hz. On the other hand, the frequency of a human daily motion is usually lower than 6Hz. Therefore, the vibrational component and the component of the user's motion intention are extracted from $\boldsymbol{X}_d$ by using the band pass filter (BPF) and the low pass filter (LPF). The controller treats the sum of the component extracted by LPF (the user's motion intention) and the opposite phase vector of the component extracted by HPF (the essential tremor) as the desired hand position vector instead of $\boldsymbol{X}_d$ in eq. (3). The vibration caused by the tremor at hand position is suppressed by adding the opposite phase vector of the component extracted by HPF [11].

In addition, the vibration caused by the essential tremor is reduced at the position of a tool grasped by the user [11]. The tool position means the position of the center of gravity (COG) which is recognized and calculated with a stereo camera. In this case, the position of the COG is calculated under the assumption that the density is the same at any points of the grasped tool.

$\boldsymbol{r}_{tool}$ is the tool vector from the hand position to the tool position and Σ_r is the coordinate frame at hand as shown in Fig. 2. The hand position can be calculated based on joint angles measured by encoders and potentiometers of each joint. We assume that $\boldsymbol{r}_{tool}$ is not affected by the vibration of the essential tremor. The vibrational component at the tool position is extracted from the tool vector by using the BPF. The suppression control at tool position is performed based on this extracted component.

$${}^{r}\boldsymbol{F}_{r,v} = -\boldsymbol{B}_{r,v}\,{}^{r}\dot{\boldsymbol{r}}_v - \boldsymbol{K}_{r,v}\,{}^{r}\boldsymbol{r}_v \tag{4}$$

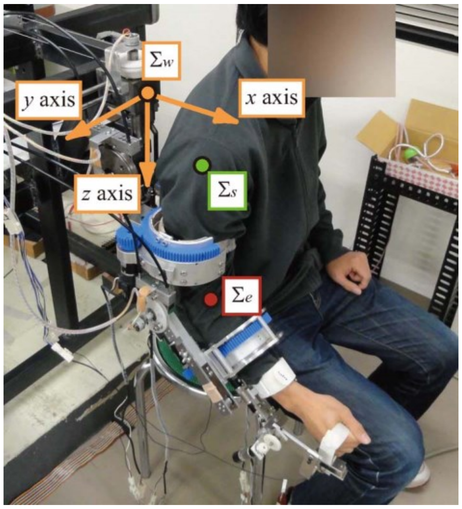

Fig. 3 Coordinate frames.

where $\boldsymbol{r}_v$ is the vibrational component at the tool position. $\boldsymbol{B}_{r,v}$ and $\boldsymbol{K}_{r,v}$ are the viscous coefficient matrix and the spring coefficient matrix, respectively. The tremor suppression torque vector at tool position is calculated with the product of ${}^{r}\boldsymbol{F}_{r,v}$ and the Jacobian matrix.

B. Suppression control at elbow position

In previous section, the controller focused the target on the hand and the tool positions to suppress the vibration of the essential tremor. However, the vibration of other part such as the elbow position still might occur. To suppress the vibration of the other part, the suppression control using the null space of the pseudo-inverse matrix is proposed in this paper.

To assist human upper-limb motions, the robot has seven motors. On the other hand, the hand force vector consists of only 6DOF. Therefore, the Jacobian matrix $\boldsymbol{J}$ used in eq. (1) is a 6*7 matrix. A pseudo-inverse matrix is used for calculation of $\boldsymbol{J}^{-1}$ in eq. (1). The null space of a pseudo-inverse matrix has been used for the optimization, vibration suppression and so on [12, 13]. In this paper, the vibration of elbow position is suppressed using the null space of the pseudo-inverse matrix. The hand force vector $\boldsymbol{F}_{end}$ in eq. (1) is rewritten as follows.

$$\boldsymbol{F}_{end} = \boldsymbol{J}^{+\mathrm{T}}\boldsymbol{\tau} + (\boldsymbol{I}_6 - \boldsymbol{J}^{+}\boldsymbol{J})\boldsymbol{\eta} \tag{5}$$

where $\boldsymbol{J}^{+}$ is the pseudo-inverse matrix of $\boldsymbol{J}$, $(\boldsymbol{I}_6\text{-}\boldsymbol{J}^{+}\boldsymbol{J})\boldsymbol{\eta}$ represents the null space and $\boldsymbol{\eta}$ is an arbitrary vector.

The coordinate frames Σ_w, Σ_e and Σ_s are defined as shown in Fig. 3. Σ_w is the global coordinate frame fixed on the frame. Σ_s is the coordinate frame fixed on the shoulder. x axis is the shoulder horizontal rotation axis, y axis is the shoulder vertical rotation axis and z axis is the shoulder internal/external rotation axis. Σ_e is the moving coordinate frame on the elbow. The desired elbow position can be calculated in the same manner as eq. (1).

$$\boldsymbol{F}_{elbow} = \boldsymbol{R}_e \boldsymbol{J}_e^{-\mathrm{T}} \boldsymbol{\tau}_e \tag{6}$$

where $\boldsymbol{\tau}_e = [\tau_1\ \tau_2\ \tau_3]^{\mathrm{T}}$ is the joint torques. τ_1-τ_3 are shoulder vertical and horizontal flexion/extension torques, shoulder internal/external rotation torque, respectively. $\boldsymbol{J}_e$ is the 3*3 Jacobian matrix from the origin to elbow joint and $\boldsymbol{R}_e$ is the rotation matrix from Σ_w to Σ_e. In addition, the robot does not generate the force along x_e, and the moments about y_e and z_e because of the mechanical limitation. Therefore, the force vector at the elbow joint is defined as $\boldsymbol{F}_{\mathrm{elbow}} = [f_y\, f_z\ n_x]^{\mathrm{T}}$. Then, the desired acceleration vector at the elbow is calculated as follows.

$$\ddot{\boldsymbol{X}}_{e,d} = \boldsymbol{M}_e^{-1}\boldsymbol{F}_{e,avg} \tag{7}$$

where $\boldsymbol{F}_{e,avg}$ is average of $\boldsymbol{F}_{elbow}$ in N_f number of samples. $\ddot{\boldsymbol{X}}_{e,d}$ and $\boldsymbol{M}_e$ are the desired acceleration vector at the elbow joint and the weight matrix, respectively. The desired velocity vector $\dot{\boldsymbol{X}}_{e,d}$ and position vector $\boldsymbol{X}_{e,d}$ at the elbow joint can be calculated based on eq. (7). However, $\boldsymbol{X}_{e,d}$ might include the influence of the essential tremor. The vibrational component of $\boldsymbol{X}_{e,d}$ is extracted by using the BPF as well as $\boldsymbol{X}_d$. $\boldsymbol{X}_{e,v}$ represents this vibrational component. In order to suppress $\boldsymbol{X}_{e,v}$, following equation is calculated.

$$\boldsymbol{F}_{e,v} = -\boldsymbol{B}_{e,v}\dot{\boldsymbol{X}}_{e,v} - \boldsymbol{K}_{e,v}\boldsymbol{X}_{e,v} \tag{8}$$

where $\boldsymbol{B}_{e,v}$ and $\boldsymbol{K}_{e,v}$ are the coefficient matrices. Equation (8) is the impedance control equation when the desired values are zero. The suppression control at elbow position is performed by applying eq. (8) to the null space in eq. (5).

IV. Experiment

To verify the effectiveness of the proposed method, the experiment was carried out. The subjects are two young healthy men. To generate the vibration of hand, the subjects performed the exercise before the experiment. In the exercise, the subject performed the elbow flexion and extension motion with a 5kg dumbbell until the subject fatigued. In the experiment, the subject wrote some sentences. Because of fatigue resulted from the exercise, the vibration occurred in the upper-limb of the subject.

The experimental results show in Figs. 4 and 5. Figure 4 shows the vibrational component at the elbow position, and Fig. 5 shows the vibrational component at the hand position. In Figs. 4 and 5, the red solid lines show the experimental result when the suppression control at hand and tool positions was performed. In contrast, the black solid lines show the experimental result when the suppression control at elbow position in addition to hand and tool positions was performed. Tables II and III show the average values of the amplitude of vibration of elbow and hand positions.

As shown in Figs. 4 and 5, Tables II and III, the effect of the tremor suppression at hand position is almost equal between both methods. However, at elbow position, the amplitude of the vibration became smaller by the effect of the tremor suppression of the proposed method. In this paper, although we are focused on the elbow position, it is thought that the proposed method can suppress other part by changing the target point depending on the part in which the tremor occurs, and be used to reduce the vibration of other involuntary motion by changing a frequency range of BPF.

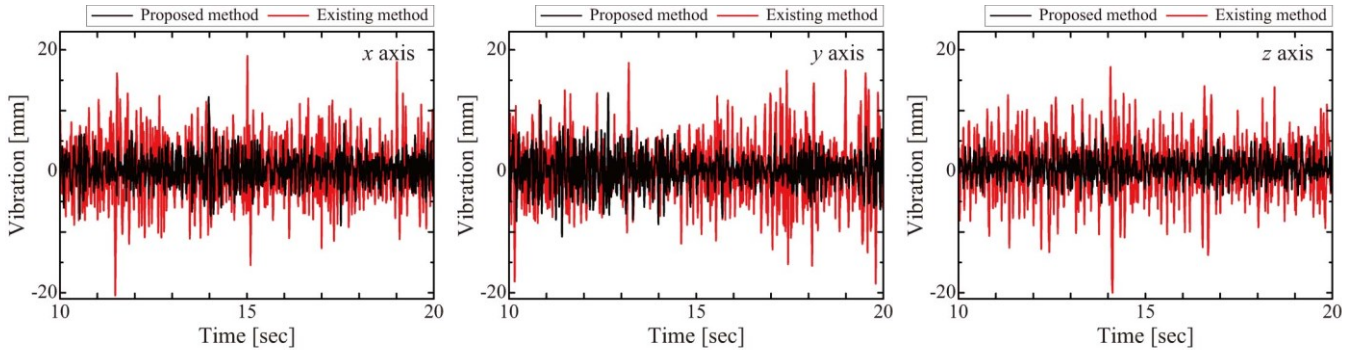

Fig. 4 The vibrational component at the elbow position.

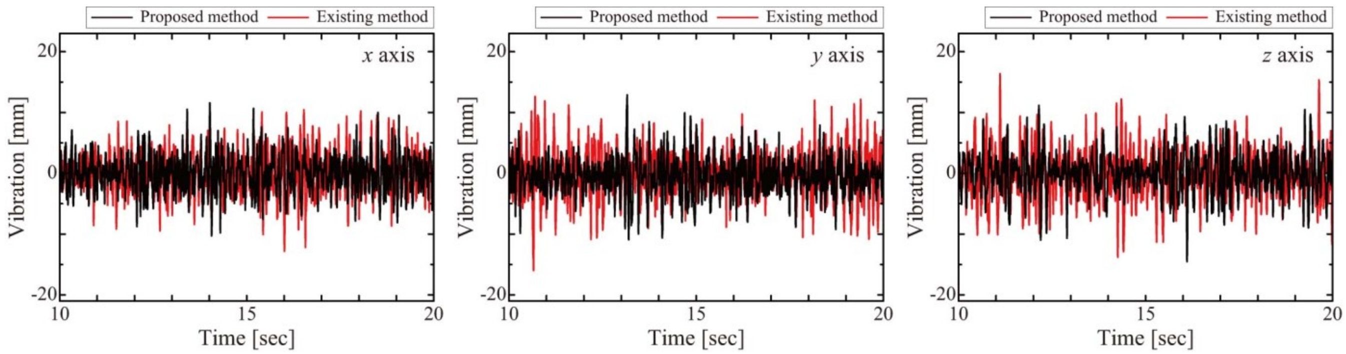

Fig. 5 The vibrational component at the hand position.

Table II The average of the amplitude of vibration of elbow position.

	x axis [mm]	y axis [mm]	z axis [mm]
Existing method	3.73	3.75	3.61
Proposed method	1.86	2.41	1.47
ratio [%]	49.8	64.2	40.8

Table III The average of the amplitude of vibration of hand position.

	x axis [mm]	y axis [mm]	z axis [mm]
Existing method	2.60	3.00	3.18
Proposed method	2.44	2.72	2.51
ratio [%]	93.6	90.7	78.8

V. CONCLUSION

Since the essential tremor affects EMG signals, the EMG-based power-assist robots might misunderstand a user's motion intention if the user suffers from 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 vibration of the elbow position is suppressed by using the null space of the pseudo-inverse matrix in addition to the hand position and the tool position. The validity of the proposed method was verified by the experiments. In the future work, the effectiveness of the proposed method is verified by performing the experiments with persons who suffer from the essential tremor disorder.

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