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Measurement and analysis of upper-limb essential tremor motion for tremor suppression with an exoskeleton robot

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Abstract: An essential tremor is one of the most common tremor disorders of the arm and it may occur during a voluntary motion. Power-assist robots are useful for the physically weak persons to perform the daily motion. Although some power-assist robots are controlled based on electromyogram (EMG) signals, EMG signals are also influenced by the essential tremor. Therefore, when the user who suffers from the tremor uses the EMG-based controlled power-assist robot, the robot might magnify the vibration of the tremor. Although the tremor suppression control has been proposed for the EMG-based controlled power-assist robot to suppress the tremor in the hand position, the other part of the upper-limb might still vibrate since actual tremor movement of the upper-limb has not been analyzed precisely. Therefore, an upper-limb tremor sensing system is proposed to measure and analyze the precise tremor motion in this paper.

Keywords: essential tremor, power-assist robot, electromyogram, tremor sensing system

1 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 amount of EMG signal is related to the muscle activity level, the EMG signal is affected not only a voluntary motion but also an involuntary motion. Therefore, the involuntary motion might be misunderstood as the user’s motion intention in the EMG-based controlled 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 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. To suppress a tremor, many methods have been proposed [1,2]. For example, Kiguchi et al. proposed the tremor suppression control method that extract the vibrational component of the estimated motion using band pass filter, and suppress the tremor by adding opposite phase force vector [3]. However, this method focused on only the estimated motion of the hand and the tremor motion of the elbow or the shoulder is not taken into consideration. Therefore, the other part of the upper-limb might still vibrate since actual tremor movement of the upper-limb has not been analyzed precisely yet.

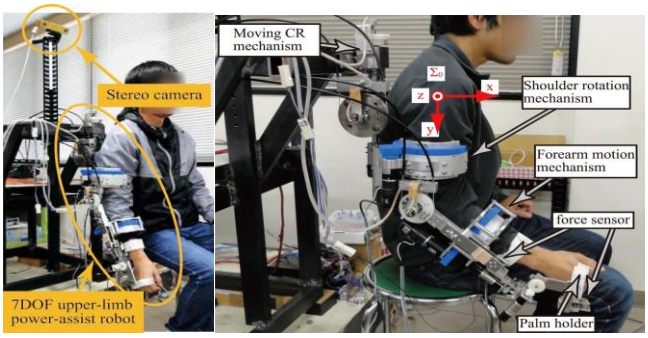

Fig. 1 7DOF upper-limb power-assist exoskeleton robot

Although there are a lot of researches of the essential tremor [4-6], there are no research which investigated about the relationship of the motion of hand, elbow, and shoulder. Therefore, an upper-limb tremor sensing system, which consists of three acceleration sensors, a gyroscope, and an encoder, is proposed to measure and analyze the precise tremor motion in this paper.

2 UPPER-LIMB POWER-ASSIST EXOSKELETON ROBOT

The 7DOF exoskeleton power-assist robot [3] for the upper limb used in this paper is shown in Fig1. The robot consists of seven DC motors. This robot is able to assist the most of each human upper-limb joint motion (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).

3 EMG-BASED CONTROL METHOD

To estimate the user's motion and control the 7DOF upper-limb power-assist exoskeleton robot, sixteen channels of EMG signals are used as main input signals.

Since raw EMG signals are not suitable as input signals to the controller, the feature of the raw signal must be somehow extracted. In order to extract the feature of the raw EMG signal, the root mean square (RMS) of the EMG signal is calculated and used as an input for the controller. The RMS calculation is written 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*) and 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:

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

where 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 [3] 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. τ is transferred to the hand force vector of the user as follows:

$$F_{end} = J^{-T}\tau \tag{3}$$

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

where F_{end} is the hand forece vector, J is the Jacobian matrix, F_{avg} is average of F_{end} in N_f number of samples. Then, the hand acceleration vector can be calculated based on eq.(4).

$$\ddot{X}_d = M^{-1}F_{avg} \tag{5}$$

where $\ddot{X}_d$ is the desired hand acceleration vector, and 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 F

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

where B is the viscous coefficient matrix and K is the spring coefficient matrix. The impedance parameters B and 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 B and K are defined based on the upper-limb posture and activity levels of activated upper-limb antagonist muscles.

Finally, the joint torque command vector τ_{motor} is calculated as follows:

$$\tau_{motor} = \kappa J^T F \tag{7}$$

where κ is the power-assist rate. When the user's muscle activation levels are low, force/torque sensor-based control is used to control the robot.

4 EXPERIMENT.

The tremor is somewhat rhythmic motion that may occur in various body parts. Especially, an essential tremor is one of the most common tremor disorders of the upper-limb and it may occur during a voluntary motion. If the essential tremor occurs in the upper-limb movement, the person may not be able to achieve target task properly. There are various researches in regard to the tremor motion of upper-limb. Although the hand motion of tremor has been analyzed up to the present, the detailed tremor motions such as amplitude of vibration, angular velocity, angular acceleration of the shoulder, the elbow, and the wrist joint have not been analyzed. Therefore, in this paper, the upper-limb tremor sensing system which consists of three acceleration sensors, a gyroscope, and an encoder is proposed to measure the tremor motion precisely.

4.1 Experiment equipment

The upper-limb tremor sensing system developed in order to measure tremor is shown as Fig.2. The accelerometer was attached in the elbow, the wrist, and the hand. Moreover, the encoder was attached center of rotation of an elbow. Moreover, the gyroscope was attached in order to measure the angle of 3 DOFs of the shoulder, and the acceleration of an elbow to the upper arm side of an elbow. Since the frequency of the essential tremor 5 to 12 Hz, the band pass filter (5 to 12Hz) is applied to the output of the accelerometers. In order not to restrict a patient's motion, it was made by not using metaled frame as much as possible, and sensors were attached on the human’s body directly. However, the encoder which measures angle of rotation of an elbow was attached on the aluminum frame. Moreover, since a wrist had the unstable surface, the accelerometers in the wrist part were attached on the plastic plate. The initial posture of elbow was set to be 90[deg] to avoid a singular configuration when the elbow was extended. The initial postures of the other joints were determined to be 0[deg] in the model of Fig.3. Moreover, I got the subject to take care so that an elbow may not be lengthened. Moreover, in order to avoid a problem of the singular configuration due to the attached position of the singular configuration due to the attached position of an accelerometer, two accelerometers are applied to compensate each other in the proposed system such as Fig.2 right side picture. Since the distal part from the wrist, angular information was calculated by integrating the angular acceleration obtained by the accelerometers of an elbow, a wrist, and a hand.

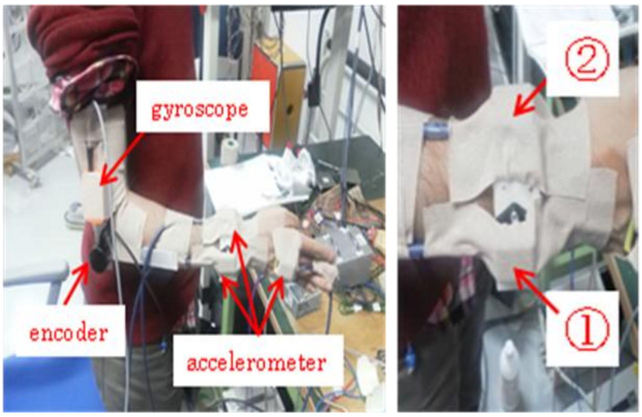

Fig.2 Experiment equipment (left: overall, right: wrist)

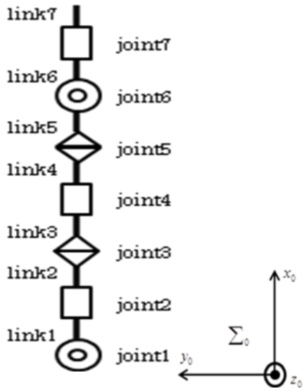

Fig.3 Model of upper-limb

Table.1 D-H parameter

i	a_i	α_i	d_i	θ_i
1	0	0°	0	q_1
2	0	90°	0	90° $+q_2$
3	0	90°	l_u	180° $+q_3$
4	0	90°	0	180° $+q_4$
5	0	90°	l_f	90° $+q_5$
6	0	90°	0	90° $+q_6$
7	0	90°	0	q_7

4.2 The analysis method

The method that calculate the position, the velocity, the accelerometer of an elbow, a wrist, a hand, and angle, angular velocity, angular accelerometer of a shoulder, an elbow, a wrist is explained in this section. The model of upper arm is shown as Fig.3. The coordinate frame Σ_0 in Fig. 3 is a coordinate frame fixed to the shoulder. The coordinate frame fixed to the shoulder is the same as the initial posture of the joint 1. Joint1-7 represent shoulder abduction/adduction, shoulder flexion/extension, shoulder internal/external rotation, elbow flexion/extension, forearm supination/pronation, wrist palm flexion/extension, and wrist palm radial/ulnar deviation, respectively. The D-H parameters were defined as shown in Table.1.

4.2.1 The calculation method of each angular information

The angles of joint1, joint2, joint3, and joint4 can be calculated based on the value acquired from the angle sensor. The angular velocity of joint1, joint2, joint3, joint4 are calculated by differentiating the angle as follows:

$$\dot{q}_{1\sim4}^{i+1} = (q_{1\sim4}^{i+1} - q_{1\sim4}^{i}) / \Delta t \tag{8}$$

where i is the number of times of measurement and Δt is sampling time. Sampling time is 0.01[sec]. Since the angle sensor was not attached for the joint5-7 in order not to restrict the patient’s motion, the value of the accelerometer was changed into angular acceleration using the following equation, and the angle and angular velocity are calculated by integrating the angular acceleration using the eq.(10) and a eq.(11).

$$\begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \\ \ddot{q}_3 \\ \ddot{q}_4 \\ \ddot{q}_5 \\ \ddot{q}_6 \\ \ddot{q}_7 \end{bmatrix}^i = J^{-1}\left(\begin{bmatrix} \ddot{x}_h \\ \ddot{y}_h \\ \ddot{x}_w \\ \ddot{y}_w \\ \ddot{z}_w \\ \ddot{y}_e \\ \ddot{z}_e \end{bmatrix}^i - \dot{J}\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \\ \dot{q}_4 \\ \dot{q}_5 \\ \dot{q}_6 \\ \dot{q}_7 \end{bmatrix}^i\right) \tag{9}$$

$$\dot{q}_{5\sim7}^{i+1} = \ddot{q}_{5\sim7}^{i} \times \Delta t + \dot{q}_5^{i} \tag{10}$$

$$q_{5\sim7}^{i+1} = \frac{1}{2} \times \ddot{q}_{5\sim7}^{i} \times (\Delta t)^2 + q_{5\sim7}^{i} \times \Delta t + q_{5\sim7}^{i} \tag{11}$$

where J^{-1} is the inverse jacobian matrix, which is 7×7 matirix, and $\dot{J}$ is the differentiated jacobian matrix. As shown in eq.(9), it was calculated using the acceleration of 2 axes of a hand's x and y, the acceleration of 3 axes of a wrist, and the acceleration of 2 axes of y of an elbow, and z. In regard to the accelerometers of the wrist, accelerometer1 in Fig.2 becomes singular configuration when $q_5 = 0[\deg]$, and accelerometer2 becomes singular configuration when $q_5 = \pm 90[\deg]$. Therefore when $-80 < q_5 < 80[\deg]$, the accelerometer2 was used, and when $q_5 < -80[\deg]$, $q_5 > 80[\deg]$, the accelerometer1 was used.

4.2.2 The calculation method of other information

All of the position, the velocity, and the acceleration of hand, wrist, and elbow were changed into the value in the fixed coordinate frame of the shoulder. The homogeneous transformation procession and the rotating matrix were calculated with D-H parameters in Table1.

4.3 Experiment results

The effectiveness of the developed upper-limb tremor sensing system was confirmed with a healthy human subject as a first step. Healthy person wore an experiment equipment, and moved arm in the various directions at random. The calculated result of elbow position is shown in Fig. 4. The calculated result of wrist position is also shown in Fig.5. As shown in Fig.4, and Fig5, the position of elbow and wrist were calculated precisely from q1-q4 which is taken by attached angle sensor. However, q5-q7's angular information were not calculated precisely. For the reason of this result, the instability of the surface human's skin is considered to be the cause. Because the noise caused by the accelerometers attached on the unstable surface of the subject skin is accumulated. As a future work, the attachment method of accelerometers must be considered so that the data of acceleration can be acquired correctly.

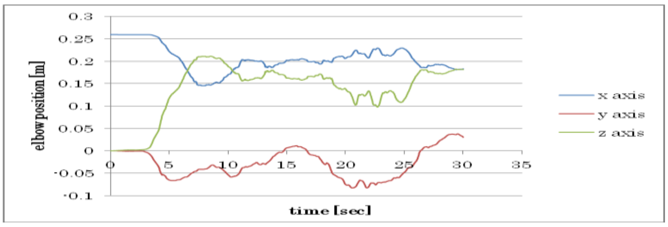

Fig.4 Elbow position

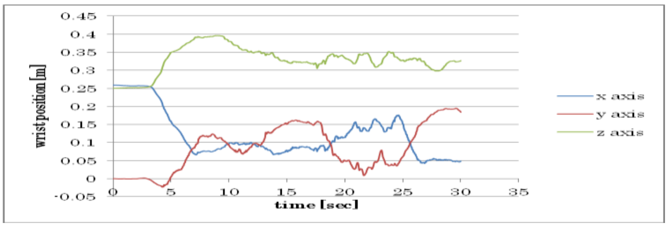

Fig.5 Wrist position

5 CONCLUSION.

In this paper, the upper-limb tremor sensing system which consists of three acceleration sensors, a gyroscope, and an encoder is proposed to measure the tremor motion. The effectiveness of the developed system was evaluated by performing experiments with a healthy human subject. As a result, the position of elbow and wrist is calculated precisely, although q5-q7 could not be calculated precisely since attachment of accelerometers were unstable. As a future work, the attachment method of accelerometers must be considered.

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