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Analysis of EMG signals of Patients with Essential Tremor Focusing on the Change of Tremor Frequency

Yuya Matsumoto, Masatoshi Seki, Takeshi Ando, *Member*, *IEEE*, Yo Kobayashi, *Member*, *IEEE*
Hiroshi Iijima, Masanori Nagaoka, Masakatsu G. Fujie, *Fellow*, *IEEE*

***Abstract*— Essential tremor is a disorder that causes involuntary oscillations in patients while engaging in actions or while maintaining a posture. ET patients have serious difficulties in performing activities of daily living such as eating food, drinking water, and writing. We have thus been developing an EMG-controlled exoskeletal robot to suppress tremors. The EMG signal of ET patients involves a mix of voluntary movement and tremor signals. To control the exoskeletal robot accurately, tremor signals must be removed from the patient's EMG signal. To date, we have been developing a filter to remove tremor signals from the patient's EMG. The design of this filter was based on the hypothesis that the rectified tremor signals are able to be approximated by a powered sine wave. This filter was found to have a large effect on removing tremor signals. However, tremor signals are generated both while performing voluntary movement and while maintaining a posture, and the filter was attenuating both signals. To control this robot accurately, the signal generated while performing voluntary movement is expected not to be attenuated. To accomplish this, we try to use a parameter that reflects a state of the patient's movement, performing a voluntary movement or maintaining a posture, as a switch to activate the powered sine filter. This paper provides an analysis of the favorable parameters. We focus on two parameters: the peak-to-peak interval of the rectified EMG signal, and the interval of the flat and low amplitude area of the rectified EMG signal. Through evaluation, it is affirmed that both parameters change with the state of the patient's movement. However, the latter parameter is superior to the former in terms of variability, which indicates that the interval of the flat and low amplitude area of the rectified EMG signal is a more favorable parameter to promote control of the exoskeletal robot. As a future work, we will mount the parameter to the algorithm and evaluate the robotic system.**

I. INTRODUCTION

A. Essential Tremor (ET)

A tremor is an involuntary oscillation of part of the body and is the most common of all involuntary movements [1]. Especially, Essential Tremor (ET) is the most widely known disorder in which tremor symptoms are indicated while performing an action or maintaining a posture, and elderly people are often ET patients – including some 4 million in Japan (about 5% of the total population). While ET is not a life-threatening disorder, it may result in functional disability and social inconvenience. In most cases, the amplitude of the tremors experienced by ET patients is considerable. About 65% of ET patients have serious difficulties in performing daily living activities (e.g. eating, drinking, writing etc.) [2], [3].

B. Motivation

Currently, approaches to suppressing ET can be divided into two types. One is through medication to suppress the over-reaction of nerves, while the other comprises Deep Brain Stimulation (DBS). However, both these approaches have their respective problems in terms of medical side effects and invasiveness involved in implanting electrodes in the brain. Instead, some researchers use functional electric stimulation (FES) to suppress tremors [4] – [6]. However, FES creates a feeling of overstimulation and causes muscle fatigue.

As an alternative approach, we have been developing an exoskeletal wearable robot for the upper limbs to support voluntary movement among ET patients (Fig. 1). The exoskeletal robot suppresses oscillations and facilitates the patient's voluntary movement by the following two steps:

1. The exoskeletal robot constrains the patient's elbow joint mechanically and suppresses oscillations by restricting the patient's motion.
2. The exoskeletal robot estimates the patient's voluntary motion which is restricted by the constraint, and follows the estimated movement.

This paper especially focuses on the second step. To enable the patient's voluntary movement with the mechanical constraint, the robot needs to estimate the patient's movement accurately.

C. Related works

As a related study, Rocon et al. have developed a robotic exoskeleton for tremor patients [7]. Here, the angular velocity

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Yuya Matsumoto is with the Graduate School of Creative Science and Engineering, Waseda University, Tokyo 169-8555, Japan (e-mail: yy-matsumoto@ruri.waseda.jp). Masatoshi Seki is with the Graduate School of Advanced Science and Engineering, Waseda University, Japan. Takeshi Ando is with the Robotics Development Center, Corporate Manufacturing Innovation Division, Panasonic Corporation, Osaka, Japan, and the Faculty of Science and Engineering, Waseda University, Japan. Yo Kobayashi is with the Faculty of Science and Engineering, Waseda University, Japan. Hiroshi Iijima is with the Rehabilitation Engineering Dept., Yokohama Rehabilitation Foundation, Japan. Masanori Nagaoka is with the Department of Rehabilitation Medicine, Juntendo University Graduate School, Japan. Masakatsu G. Fujie is with the Faculty of Science and Engineering, Waseda University, Japan.

values obtained by gyro sensors implemented in each joint are used as input data to control the exoskeleton. Consequently, this robotic motion inevitably lags behind the user's motion due to inability to attain angular velocity before the start of the user's motion. Therefore, the input signal to control the exoskeletal robot needs to consist of information that can be obtained *before* the start of movement. In this study, electromyography (EMG) is used as the input signal to control the exoskeletal robot.

Many researchers use surface EMG as the input signal to control exoskeletal robots [8] – [10]. In these studies, the target users of the robot are elderly persons with weakened muscle power, upper extremity amputees, or caregivers and nurses. The EMG signals of these users contain only voluntary movement signals. However, the EMG signals of ET patients contain both voluntary movement signals and tremor signals. It was confirmed that tremor signals overlap with the EMG signals of ET patients within the range of 4–10(Hz) [11]. Tremor signals are generated involuntarily and cause an error in the estimation of voluntary movement. To control the exoskeletal robot accurately through the EMG signals of ET patients, tremor signals must be removed from the EMG signals.

Some approaches for removing tremor signals have been proposed by past researchers. Yano et al. developed an adaptive filter for force sensor data which was used in admittance control for the meal-assist manipulator [12], [13]. This filter estimated the tremor frequency, and attenuated the signal in the estimated frequency band by using a band stop filter. Riviere et al. have proposed a filtering algorithm for physiological tremor arising during microsurgery [14]. The above studies purposed on reduction of tremor noise in motion signals measured by a force sensor, position meter, etc. In these signals, effects of tremor are observed as additive noise. Therefore, once the noise frequency has been detected, it is easy to design a real-time processing system.

On the other hand, it can be anticipated that tremor effect in EMG signals is a multiplicative noise [15] because rhythmic muscle contractions and relaxations do not cause EMG offset ups and downs but cause amplitude fluctuation. For the reduction of multiplicative noise, the Cepstral Mean Normalization [16] (CMN) and maximum a posteriori estimation CMN (MAP-CMN) are widely recognized. CMN is not a real-time adapted method. MAP-CMN needs Cepstral Mean calculations from a signal of sufficient length to provide superior performance.

Figure 1 Exoskeletal robot for ET patients

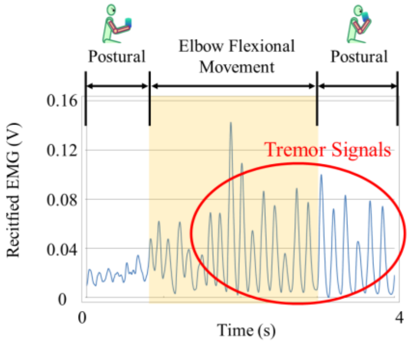


Figure 2 The EMG signal of an ET patient. Tremor signals overlap the EMG signal both while performing a voluntary movement and while maintaining a posture.

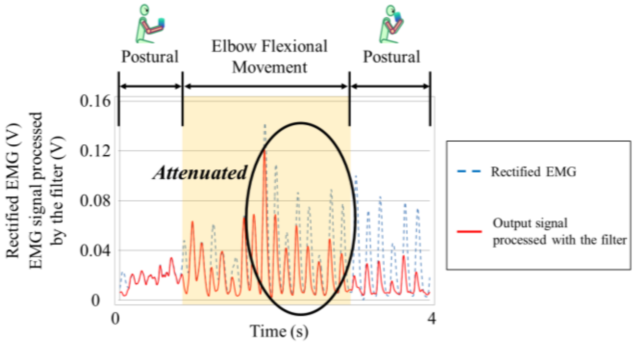


Figure 3 The effect of the powered sine filter proposed in our previous papers. Not only the tremor signals generated while maintaining a posture but also the signals generated while performing a voluntary movement are attenuated.

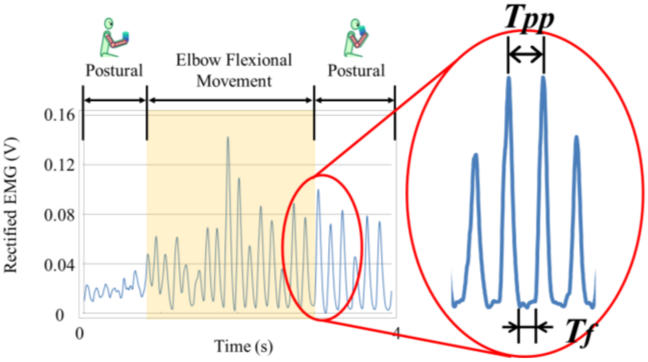


Figure 4 The examined parameters in this paper. T_{pp} refers to the peak-to-peak interval of the rectified EMG signal. T_f refers to the interval of the flat and low-amplitude area of the EMG signal.

D. Objectives

We are in the process of developing a real-time tremor-removing filter [17] – [19]. This filter was designed based on the hypothesis that rectified tremor signals are able to be approximated by a powered sine wave; that is, high correlation between both signals leads to high attenuation of tremor signals, while low correlation leads to low attenuation. This filter had a large effect on removing tremor signals from the EMG signals. However, tremor signals are generated both while performing a voluntary movement and while maintaining a posture (Fig. 2). Accordingly, this filter attenuated not only tremor signals generated while maintaining a posture but also those generated while performing a voluntary movement, and caused estimation error in the voluntary movement (Fig. 3). To reduce the estimation error, attenuation of the signals generated while performing a voluntary movement must be diminished.

To achieve this, we use the tremor signal frequency as a switch to activate the powered sine filter [20]. From the experiment, we confirm that the frequency of tremor signals varies depending on the state of a patient's movement. The frequency while maintaining a posture is lower than that while performing a voluntary movement. We set a threshold for the frequency and established an algorithm to activate the powered sine filter only when the threshold condition was satisfied. This approach succeeded in attenuating only the tremor signals generated while maintaining a posture. However, the calculated frequency varied widely, and this variability causes the limited effect; that is, in some movement, only the tremor signals generated while maintaining a posture are attenuated, and in some other movement, the signals generated both while performing a voluntary movement and while maintaining a posture are attenuated. To resolve the limitations, a parameter that can satisfy the following two conditions is required:

1. The parameter's value changes with the state of the patient's movement.
2. The parameter's value does not vary widely.

Consequently, the objectives of this paper are to analyze favorable parameters that satisfy the aforementioned two conditions. Specifically, we focus on two parameters. One is the frequency of tremor signals, which is described as T_{pp} in Fig. 4. Although this parameter was discussed in our previous paper, we confirm through re-examination that one of the reasons the frequency varied widely was to do with the function used to calculate the frequency. Therefore, in this paper, the frequency T_{pp} is calculated by using another approach. The other parameter is an interval of a flat and very low-amplitude part of tremor signals, which is described as T_f in Fig. 4. From qualitative observation of the EMG signals of ET patients, it is considered highly likely that the interval T_f changes with the state of the patient's movement. Accordingly, we select the interval T_f as the examined parameter.

This paper is structured as follows: Section II describes the experimental methodology to analyze the characteristic of each of the parameters. The function to calculate each parameter is described in this section. Section III provides the result and discusses the experiment. Section IV forms the conclusion of this paper and discusses future works.

II. THE EXPERIMENTAL METHODOLOGY

A. Experimental Objective

In this experiment, we analyze the characteristic of the favorable parameter described briefly in Section I. Through the experiment and the analysis, we leverage the characteristic to promote control of the exoskeletal robot for ET patients.

Here, in the medical field, the frequency is said to be almost constant in each patient [21], [22]. However, as stated in Section I, it seems that the frequency of tremor signals changes with the state of the patient's movement. Most previous studies on the frequency of tremor signals reported only the frequency while maintaining a posture because ET has especially strong oscillations while maintaining a posture. Few studies reported the frequency measured in the experiment whose task contained both performing voluntary movement and maintaining a posture. Also, the characteristic of the interval T_f is rarely reported. Therefore, the result of this experiment is thought to be valuable in terms of new knowledge about ET patients.

B. Subject

The subject of this experiment was one ET patient (male, 70 years old) who had tremor symptoms, especially in forearm rotation and elbow flexion/extension. Tremor signals in EMG signal are measured from the biceps brachii. We gave the subject a detailed account of our experimental objectives, made it clear that he was entitled to stop the experiment whenever he desired, and obtained his consent. Furthermore, he practiced the elbow flexional movement in advance of the experiment to get used to the experimental movement. This experiment was approved by the Institutional Review Board in Waseda University.

C. Protocol to Acquire the EMG Signal of ET Patients

The measurement of EMG signal was conducted twice on different days. The subject performed an elbow flexional movement while holding a bottle filled with water (weight: 550g), and also while holding an empty bottle (weight: less than 10g) to simulate the movement of drinking water. At this point, the target movement time was fixed on 1.25s throughout the practice, and this pace was maintained using a metronome. The subject performed the experimental movement 10 times with each bottle (Total 20 times/day). The EMG signals were obtained through surface electrodes (Biometrics Ltd.) and DataLog (Biometrics Ltd.) and sampled at the rate of 1000Hz. The electrodes were placed on the biceps brachii, with their positions determined by an occupational therapist. The elbow angle was obtained with a goniometer (Biometrics Ltd.), and was also sampled at the rate of 1000Hz. The voluntary movement of the subject was determined by the elbow angle obtained with the goniometer.

D. Pseudo Differential

To calculate the frequency of tremor signals, and the interval of a flat and very low-amplitude part of the EMG signal, a differential of the EMG signal is used. We use the pseudo differential. The transfer function of the pseudo differential is described as follows:

$$Y / X = s / (1+T_d*s) \tag{1}$$

where T_d refers to the time constant. In this experiment, Td is set to 20ms by trial and error. Here, we conduct s-plane to z-plane transform based on the backward difference. The equation of this transform is as follows:

$$s = (1 - z^{-1}) / \Delta T \tag{2}$$

where ΔT refers to the sampling time, 1ms. Finally, (2) is substituted into (1). The calculated differential at time t = n is as follows:

$$y_n = (x_n - x_{n-1} + T_d * y_{n-1}) / (\Delta T + T_d) \quad (3)$$

where y_n refers to the differential at t = n, and x_n refers to the input signal at t = n. In this experiment, the input signal was the rectified EMG signal and was processed by a low-pass filter with cutoff frequency of 100Hz and damping coefficient of 0.7.

E. The Examined Parameters

In this paper, the frequency of tremor signals is estimated by calculating the interval between their consecutive peaks (Fig. 4, T_{pp}). When the rectified EMG signal is at its peak, the differential of the rectified EMG signal inevitably crosses zero as shown in Fig. 5, left. Accordingly, the frequency is able to be estimated by the time lag between the present zero cross and a previous zero cross.

The interval of the flat and low-amplitude area of the EMG signal (Fig. 4, T_f) is also estimated using the differential of the rectified EMG signal. When the amplitude of the EMG signal is flat and low, the differential changes from negative to positive as shown in Fig. 5, right. Therefore, we set the respective threshold for both positive and negative values, and calculated the interval between the differential crossing each of the thresholds. In this experiment, the positive threshold is set to 250mV/s, and the negative threshold is set to -250mV/s.

III. RESULT AND DISCUSSION

A. Dependence on the State of the Patient's movement

Fig. 6 shows an example of the calculated parameters. Here, both T_{pp} and T_f are updated intermittently; that is, T_{pp} is updated only when the differential of the rectified EMG crosses zero, and T_f is updated only when the differential crosses the positive threshold. There, in this experiment, their latest updated value is treated as the present value of both parameters to calculate each parameter at the rate of 1ms. By this treatment, the calculated parameters are changed like a step as shown in Fig. 6.

According to Fig. 6, both T_{pp} and T_f seem to change with the state of the patient's movement. Both parameters are found to be longer while maintaining a posture than while performing a voluntary movement. To validate this characteristic in detail, we compare both the parameters under all experimental conditions, the bottle condition, and the date condition.

We analyze the signal generated around the end of the voluntary movement because tremor signals seem to be generated especially in the middle of performing a voluntary movement and while maintaining a posture. We calculate an average of the respective parameters among every 100ms, from 1000ms before the end of a voluntary movement to 1000ms after that. Fig. 7 shows the box plot of the calculated average of each parameter. Each box contains the information of all 10 movements in each condition. From Fig. 7, in all conditions, the characteristic that both T_{pp} and T_f change with the state of the patient's movement can be observed.

The fact that the characteristic is affirmed in the experiment conducted on different days indicates that it is highly likely to be repeatable and this is not a coincidence. However, the values of T_{pp} and T_f seem to change with the date; for example, T_f while maintaining a posture is longer on the first day than on the second day, on comparing Fig. 7 (b) and (f). The patient's condition and stress level are possible factors for this change. Therefore, to leverage the characteristic, each parameter must be measured before each use of the robot or on each day.

Also, the fact that the characteristic is affirmed in the experiment while holding a bottle with different weight conditions, empty or filled with water, indicates that this characteristic is unlikely to be affected by the biomechanical loading to the muscle. However, comparing Figs. 7 (a) and (c) or Figs. 7(b) and (d), the amount of change depending on the state seems to be different for each bottle condition. To verify the characterisitic regarding the weight condition in detail, further research is needed.

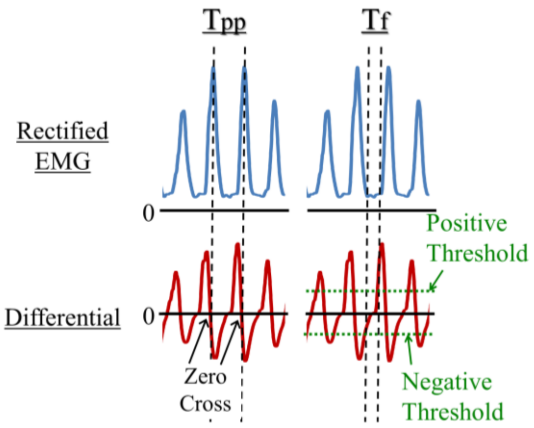


Figure 5 Landmark to calculate the examined parameters. T_{pp} is calculated by the time lag between the present zero cross and the previous zero cross. T_f is the interval from the timing when the differential crosses the negative threshold to the timing when the differential crosses the positive threshold.

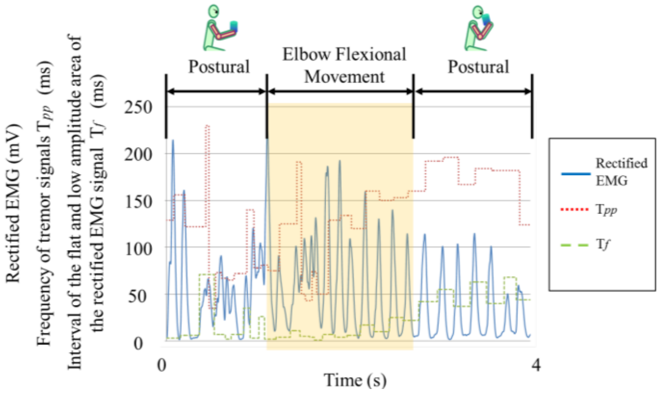
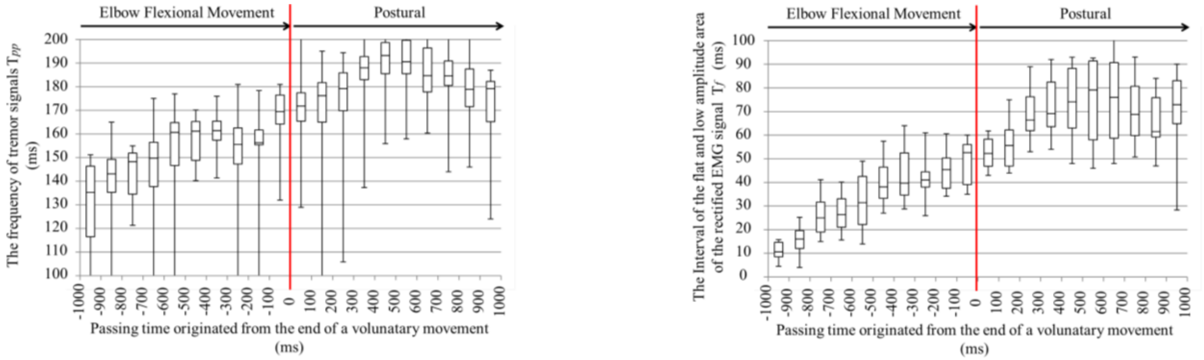
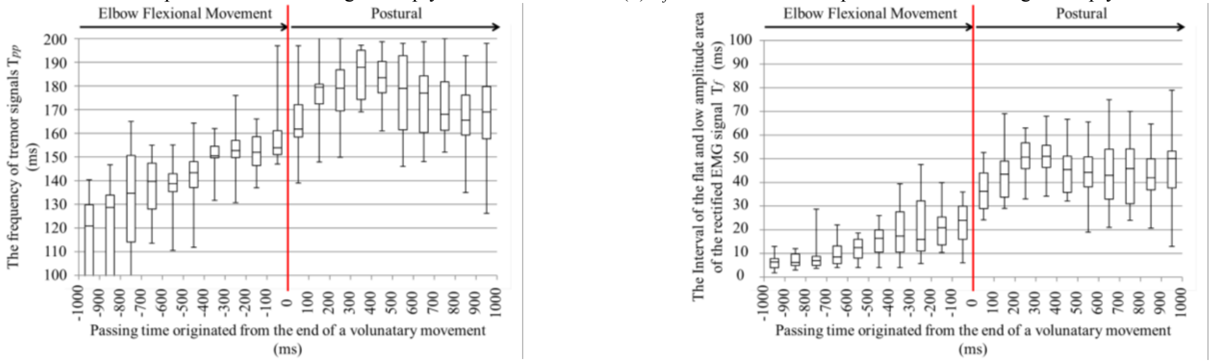


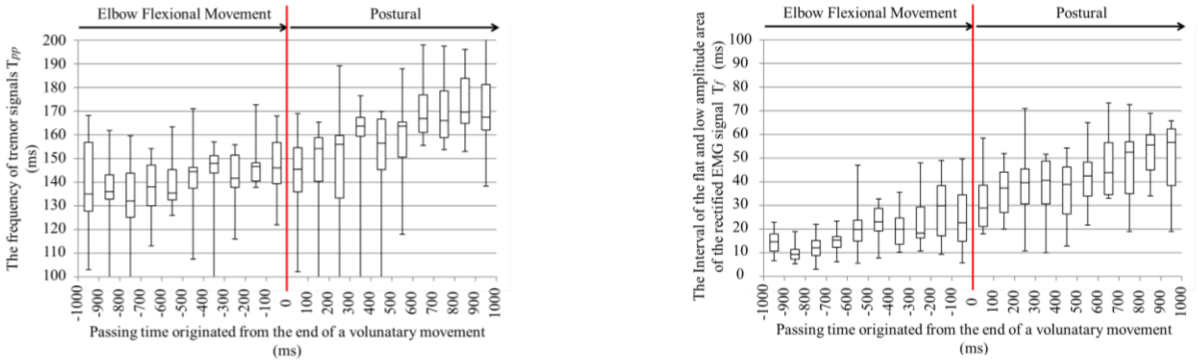
Figure 6 An example of calculated parameters. The solid blue line shows the rectified EMG signal, which is the input signal for calculating each parameter. The dotted red line shows the frequency of tremor signals, T_{pp}, and the dashed green line shows the interval of the flat and low-amplitude area of the rectified EMG signal, T_f.



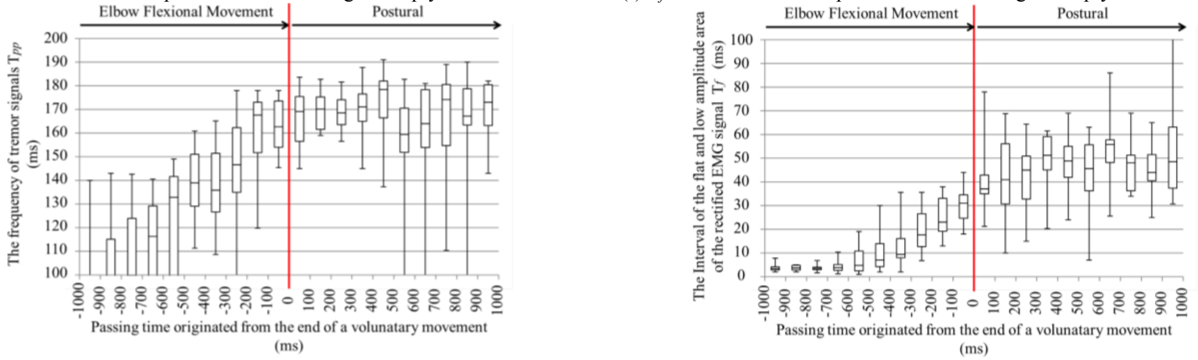
(a) T_{pp} calculated in the experiment with holding an empty bottle (b) T_f calculated in the experiment with holding an empty bottle



(c) T_{pp} calculated in the experiment with holding a bottle filled with water (d) T_f calculated in the experiment with holding a bottle filled with water

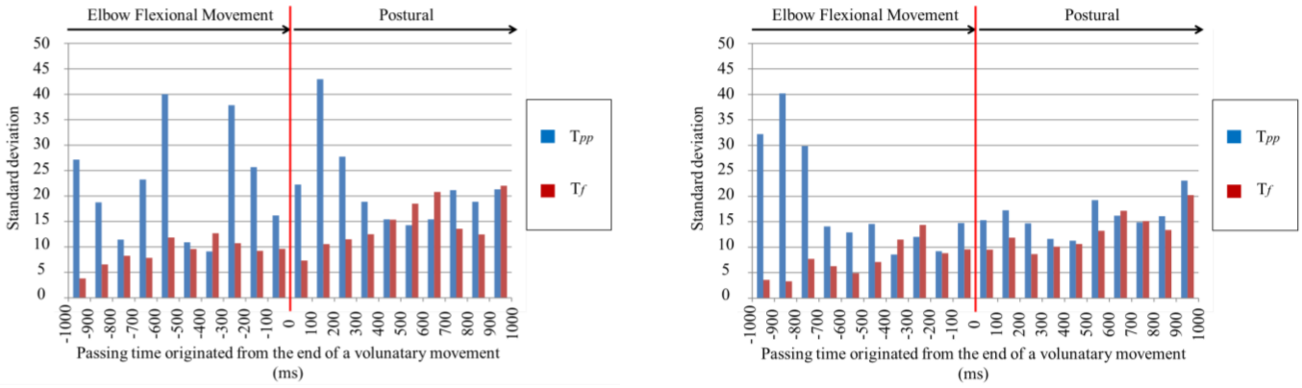


(e) T_{pp} calculated in the experiment with holding an empty bottle (f) T_f calculated in the experiment with holding an empty bottle

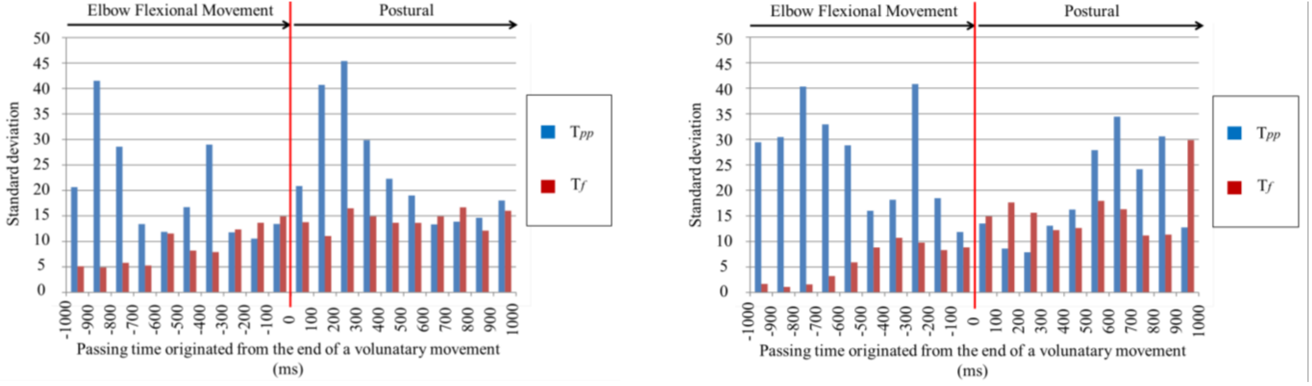


(g) T_{pp} calculated in the experiment with holding a bottle filled with water (h) T_f calculated in the experiment with holding a bottle filled with water

Figure 7 The transition of the value of each parameter. (a), (b), (c) and (d) show the result of the experiment on the first day, and (e), (f), (g) and (h) show the same for the second day. The result of the frequency of tremor signals, T_{pp}, is shown in (a), (c), (e), and (g), and that of the interval of the flat and low-amplitude area, T_f, is shown in (b), (d), (f), and (h). The horizontal axis refers to the passing time originated from the end of the voluntary movement; that is, the area of negative values and that of positive values respectively indicates the state of performing a voluntary movement and that of maintaining a posture. The vertical axis shows the value of each parameter. Each box plot is created by taking 10 movements into account.



(a) The result in the experiment with holding an empty bottle (b) The result in the experiment with holding a bottle filled with water



(c) The result in the experiment with holding an empty bottle (d) The result in the experiment with holding a bottle filled with water

Figure 8 The comparison between the frequency, Tpp, and the interval, Tf, in terms of Standard deviation. The horizontal axis shows time, which is the same as the horizontal axis of Fig. 7, and the vertical axis shows standard deviation. The blue bars show standard deviation of Tpp and the red bars show that of Tf. The experiment of the 1st day is shown in (a) and (b) and that of the 2nd day is shown in (c) and (d).

B. Variability

As described in Section I, The variability of the parameter also needs to be analyzed. We calculate the standard deviation (SD) of each parameter every 100ms, from 1000ms before the end of the voluntary movement to 1000ms after that, just as in the previous section. Fig. 8 shows the result of each condition. The blue and red bars respectively show the SDs of T_{pp} and T_f. In all conditions, SD of T_f is more stable and also less than that of T_{pp}. This result indicates that T_f is less variable than T_{pp} and that T_f is the possible parameter to leverage the robotic control.

IV. CONCLUSION AND FUTURE WORKS

ET is a disorder that causes involuntary oscillations in patients while engaging in actions or while maintaining a posture. ET patients have serious difficulties in performing activities of daily living such as eating food, drinking water, and writing. We have thus been developing an EMG-controlled exoskeletal robot to suppress tremors. The EMG signal of ET patients involves a mix of voluntary movement and tremor signals. To control the exoskeletal robot accurately, tremor signals must be removed from the patient's EMG signal.

To date, we have been developing a filter to remove tremor signals from the patient's EMG. This filter was designed based on the hypothesis that the rectified tremor signals are able to be approximated by a powered sine wave. This filter was found to have a large effect on removing tremor signals. However, tremor signals are generated both while performing voluntary movement and while maintaining a posture, and the filter was attenuating both signals. To control this robot accurately, the signal generated while performing voluntary movement is expected not to be attenuated. To accomplish this, we try to use a parameter that reflects a state of the patient's movement, performing a voluntary movement or maintaining a posture, as a switch to activate the powered sine filter. In this paper, the analysis of the favorable parameters is described.

We focus on two parameters, the peak-to-peak interval of the rectified EMG signal, T_{pp}, and the interval of the flat and low amplitude area of the rectified EMG signal, T_f. Through evaluation, it is affirmed that both parameters change with the state of the patient's movement. However, T_f is superior to T_{pp} in terms of variability. Standard deviation of T_f is less than that of T_{pp}, which indicates that T_f is a more favorable parameter to promote robotic control.

As a future work, we will mount the parameter to the algorithm and evaluate the robotic system. At the same time, we will verify the characteristic of T_f among more patients to construct a control system that can robustly accommodate the individual differences of users.

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