Performance Improvement in User Verification Using Evoked Electroencephalogram by Imperceptible Vibration Stimuli

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***Abstract*—In this study, we examine electroencephalogram (EEG) biometric information that can be detected continuously with high confidentiality to realize personal verification using the evoked EEG when presented with an imperceptible vibration stimulus. Considering the survey of conventional studies on brainwaves evoked by perceptible vibration stimulation, we determined that to use the evoked EEG, including the immediately response after the stimulus is effective in verification. Therefore, we introduce a method for repeating the stimulus presentation over a short time. In addition, to improve the verification performance, we introduce support vector machine (SVM). Furthermore, we evaluated the verification performance and obtained an equal error rate of 11%.**

***Index Terms*—biometrics, EEG, imperceptible vibration stimuli, EER, SVM**

I. INTRODUCTION

In recent years, biometric authentication, such as using fingerprint and facial information, has been employed for login authentication of smart phones. Because biometric authentication uses personal biometric information rather than memories or possessions, there is no fear of loss. However, when biometric information exposed on a body surface, such as fingerprints or face, is used, there is a risk of forgery due to camera voyeurism. In addition, because authentication is generally performed only once at the start of system usage, there is a risk of impersonation by others after the authentication, and thus, continuous authentication is required. Therefore, electroencephalogram (EEG) has garnered attention as a biometric that can be detected continuously with high confidentiality [1]. In our research, we aim to use evoked EEG by specific stimuli for authentication. In our previous study, we evaluated the verification performance using the content ratio of each frequency band of the evoked EEG spectrum as the feature value when an imperceptible vibration stimulus was presented continuously for 30 s. The results showed that the average equal error rate (EER) was 34% when the Euclidean distance pattern matching method was employed [2]. The EER is the value when the rejection rate of the user is equal to the acceptance rate of others. In this paper, we introduce a method of repeating the presentation of a stimulus for a short period of time because we believe that using the evoked EEG including the response immediately after the stimulus is more effective for verification. In addition, we introduce support vector machine (SVM) as a verification method to improve the verification.

II. PREVIOUS RESEARCH

In the previous study [2], we confirmed that there was a significant difference between the evoked EEG by an imperceptible vibration stimulus and the spontaneous EEG or that evoked by a perceptible vibration stimulus. In addition, a significant difference was observed between the evoked EEG of the subject and that of others when the subject was presented with an imperceptible vibration stimulus, indicating that the evoked EEG can be used for personal verification. Further, we evaluated the verification performance using the Euclidean distance based on the power spectrum of each frequency band of the evoked EEG as a feature and found that the EER was 34%. However, this result is still not satisfactory, and the verification performance needs to be improved.

III. IMPROVEMENT OF STIMULUS PRESENTATION METHOD

A. Investigation of evoked responses to vibration stimuli

To improve the verification performance, we investigated the knowledge of the response to the vibration stimuli and found that the response to the vibration stimuli appeared within approximately 1 s immediately after the stimuli for a short time stimuli [3], [4]. Specifically, when a perceivable oscillatory stimulus was presented, positive to negative potential changes such as P50, N70, P100, and N140 appeared approximately 50 or 100 ms after the stimulus. These are called event-related potentials (ERPs), and they are detected by averaging over 100 times. We assumed that the verification performance could be improved by using EEG that includes the immediate response to the stimulus. In this study, we investigated the evoked EEG by a short-time vibration stimulus in the same environment as in the previous study [2].

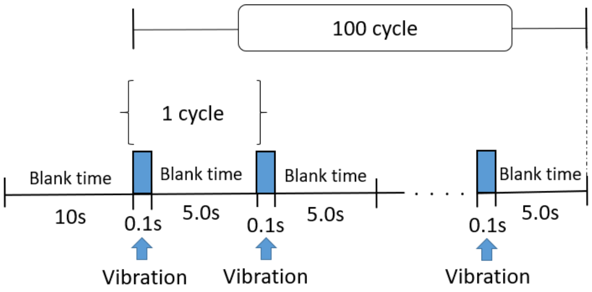

Fig. 1. Method for presenting perceivable vibration stimuli.

Fig. 2. Stimulus presentation device.

B. *Evoked responses to perceptible brief vibration stimuli*

As shown in Fig. 1, we presented 100 cycles of 0.1 s of perceivable vibration stimuli (200 Hz) with 5 s of blank periods. Fig. 2 shows the device used to present the stimuli. We used the same device as in the previous study. We made a handprint to fix the stimulus presentation position and presented the stimulus to the upper part of the palm [2]. We used Emotiv's EPOC+ (sampling frequency: 256 Hz, 14 electrodes) as the EEG sensor. The EEG was measured for five subjects in a resting, closed-eyed, seated position and with earplugs.

The EEG data for 1 s after the stimulus presentation was extracted for each cycle and averaged over 100 cycles. An example of the ERP waveform detected at electrode F3 is shown in Fig. 3. A positive potential change followed by a negative potential change was observed approximately 100 ms after the stimulus as observed in Refs. [3], [4].

C. *Evoked response to unperceivable brief vibration stimuli*

The findings in the previous section were for perceivable vibration stimuli, and it was unclear whether the same response could be obtained for imperceptible vibration stimuli. Therefore, we measured the EEG of five subjects after they were identically presented with nonperceivable vibration stimuli. The frequency of the imperceptible vibration was first set for each subject because the range of the imperceptible vibration was different for each individual. Figure 4 shows an example of the ERPs detected by electrode F3. It can be confirmed that a positive and negative potential change occurred approximately 100 ms after the stimulus when the imperceptible vibration stimulus was presented. Therefore, it was confirmed that the evoked response appeared even when the vibration stimulus was not perceived.

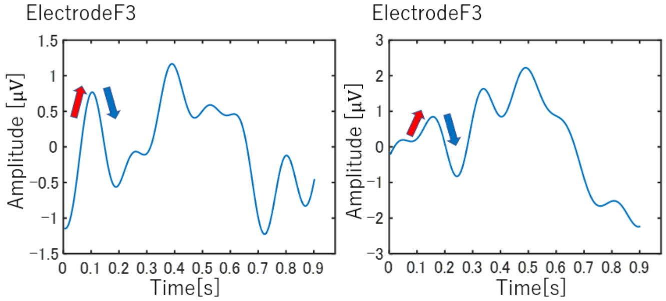

Fig. 3. ERP during the presentation of perceptible vibration stimuli.

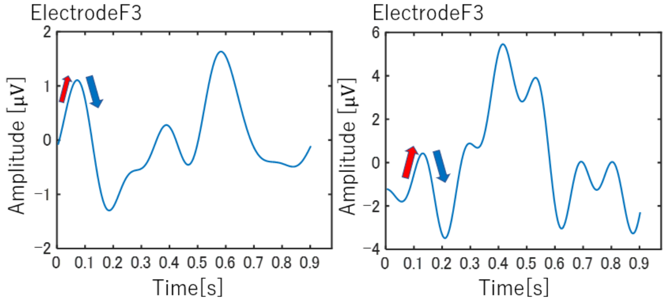

Fig. 4. ERP during presentation of unperceivable vibration stimuli.

IV. EEG MEASUREMENT

To evaluate the verification performance, we gathered evoked EEGs by imperceptible vibration stimulation.

A. *Selection of imperceptible vibration frequencies*

The frequency of the unperceivable vibration stimulus varies from subject to subject; thus, the frequency is selected for each subject. The subjects were 10 males in a resting, closed-eyed, seated position. First, their sensation thresholds were investigated. While increasing the vibration frequency by 10 Hz, the subjects were instructed to respond when they sensed the vibration. The number of measurements per subject was 15. Next, a 95% confidence interval among the sensed frequencies of each subject was calculated. 50 Hz was added to the upper limit of the 95% confidence interval, which resulted in a personalized vibration frequency for each subject.

TABLE I
MEASUREMENT CONDITION.

number of subjects	10 men
Presenting stimulus	Subject's own frequency Other people's frequencies
Number of measurements	10 stimulations for the subject One spoof stimulus × for 9 people
Measurement time	0.1s of stimulus and 5s of blank time Overall: about 50 seconds
Environment	Resting, eyes closed, seated posture, ear plugs used

B. Measurement method

We measured the evoked EEG of the subjects using a short, imperceptible vibration stimulus. The method of stimulus presentation was the same as in the previous chapter, but the number of cycles per measurement was set to 10 because short-duration measurements are typical in actual applications. Table I shows a summary of the measurement conditions. The EEG data measured by presenting the subject's own stimulus to the subject is called the genuine data, whereas those measured by presenting another person's stimulus to the subject is called the imposter data.

V. VERIFICATION PERFORMANCE EVALUATION

A. feature extraction

In this paper, the power spectral content of each frequency band of the EEG is used as the feature value, with the preprocessing being similar to that used in the previous studies [2], [5]. The four frequency bands are θ-wave (4–8 Hz), α-wave (8–13 Hz), low β-wave (13–26 Hz), and γ-wave (26–43 Hz). The content ratio is the ratio of the power spectrum of each frequency band to the sum of the power spectrum of all frequencies (4–43 Hz) [2]. Thus, the features are the four content ratios.

B. Examination of individuality of measured EEG by t-test

To confirm whether individuality exists in the EEG evoked by unperceivable brief vibration stimulation, Welch's t-test was conducted to determine whether any significant difference in the content ratio of each frequency band between the EEG of the subject and that of others when imperceptible stimulation was presented. The results of Welch's t-test showed that there was a significant difference in the content ratio of α-wave, low β-wave, and γ-wave bands between the subject's EEG and that of others [5].

C. Verification method

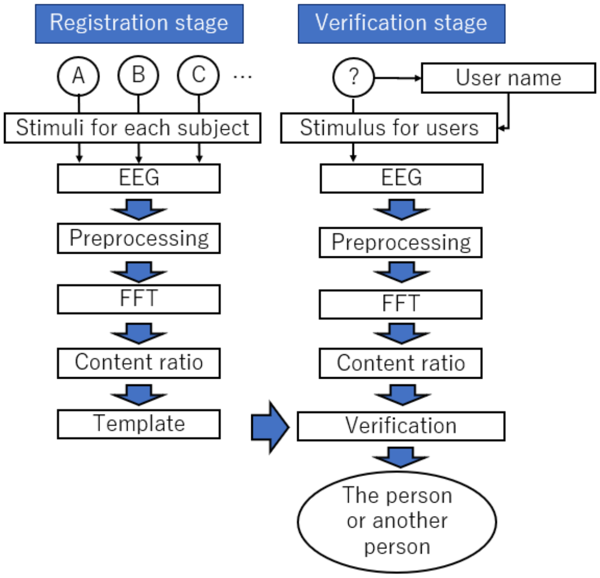

Fig. 5. Verification flow.

The flow of verification is shown in Fig. 5. During the registration stage, the EEG is measured by presenting vibrations of a set frequency for each user (subject). The measured EEG data are preprocessed as in the previous studies [2], [5], and the power spectral content of each frequency band is derived via fast Fourier transform (FFT) and subsequently stored in the system as a template. In the verification stage, the person intending to use the system presents the name of the user, and the vibration of the set frequency is introduced to the presented person; thereafter the EEG is measured. Then, the test data for verification is created via the same process as in the registration stage. Finally, the Euclidean distance between the template data and the test data is used for verification. If the distance is shorter than a predetermined threshold, the person is accepted as being a genuine user, otherwise, the person is rejected. In general, the threshold value is set to a large value when security is important and to a small value when convenience is important. The rejection of genuine users and acceptance of imposters rates are calculated when the threshold is changed, and the value when they become equal is called the EER, which is used for the evaluation of the verification performance.

D. Evaluation conditions

The dataset used included 10 genuine data and 9 imposter data for each subject. Of the 10 genuine datasets, 5 were template data, whereas the other 5 were test data. To consider the effect of the combination of template data and test data on the verification performance, we conducted five cross-validation tests in which the combination was randomized.

E. Result

To compare the results obtained with those of the previous study [2] wherein the vibration stimulus was presented continuously for 30 s, it is necessary to match the data length of the EEG. Therefore, the EEG data for 3 s immediately after the short duration vibration stimulation were connected for 10 cycles to form 30 s data. FFT was performed to derive the content ratio for the 30 s data.

The verification performance of electrodes in the previous study is shown in Table II, and the results of the proposed new stimulus presentation method are shown in Table III. Here, AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4

TABLE II
RESULTS FROM PREVIOUS RESEARCH [%] [2].

Electrodes	AF3	F7	F3	FC5	T7	P7	O1	O2	P8	T8	FC6	F4	F8	AF4	average
EER	32.5	31.1	34.0	32.9	36.9	34.6	37.6	35.0	31.9	33.8	34.0	33.8	32.2	31.5	33.7

TABLE III
RESULTS FROM THE NEW METHOD[%].

Electrodes	AF3	F7	F3	FC5	T7	P7	O1	O2	P8	T8	FC6	F4	F8	AF4	average
EER	20.4	20.5	24.6	22.7	35.3	16.2	23.8	26.6	24.6	21.0	25.9	27.2	21.6	25.2	24.0

are the names of electrodes. In addition, the average values for all the electrodes are also shown.

As evident from the comparisons, the average EER was improved to 24.0% while that of the previous study was 33.7%. This suggests that the short duration of the vibration stimulus, rather than the continuous presentation of the stimulus, comprises more evoked responses to the stimulus, resulting in higher verification performance.

VI. INTRODUCTION TO SVM

We confirmed that the use of evoked EEG by short-term vibration stimulation can improve the verification performance. However, the average EER is 24%, which is still not sufficient for verification performance. Therefore, we introduce SVM, which is a machine learning method that exhibits excellent verification performance. We use SVM^{light} as the software for SVM [6].

A. SVM

SVM is a type of machine learning method that uses supervised learning to construct a two-class pattern classifier by drawing a boundary between the two classes to be classified, while maximizing the margin using support vectors.

B. Verification method

The flow of verification is shown in Fig. 6. In this case, we construct a 1vsAll SVM to discriminate between two classes: a person and others. In the learning stage, we use the genuine data and the imposter data as the training data to learn whether the person is a genuine user. Thereafter, the same process described in the previous section is used to derive the content ratio. The SVM is trained to output "+1 " for the genuine data and "-1" for the imposter data. In the verification stage, a prospective person first specifies the name of a regular user. And, the vibration of the specified regular user is presented the prospective person. Next, the system performs a process similar to the one in the previous section, derives the content ratio, and tests whether the proppective person is a genuine user using the 1vsAll SVM model of the regular user specified by the prospective person. If the output of the SVM model is 0.5 or higher, the prospective person is accepted as a genuine user.

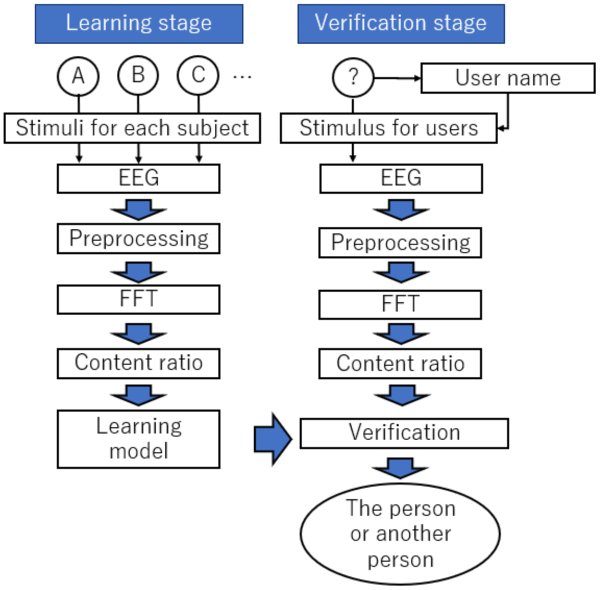

Fig. 6. SVM flow.

TABLE IV
HYPERPARAMETERS

Cost parameter	1	50	100	150	200	250
	300	350	400	450	500	
Gamma parameter	1	50	100	150	200	250
	300	350	400	450	500	

C. Evaluation conditions

We employed 5 out of 10 genuine data and 5 out of 9 imposter data for each subject as the training data. All the data that were not used as training data were used as test data. The optimal values of the kernel functions (linear kernel, polynomial kernel, and RBF kernel) and hyperparameters used in the SVM were determined via grid search. The range of hyperparameters used in this study is presented in Table IV. From this range, the optimal value was determined by brute force to minimize the EER. To consider the influence of the combination of learning and test data on the verification performance, we performed 10 cross-validation tests.

D. Result

To compare the verification performance, the EEG data for 3 s immediately after the short-time vibration stimulation were connected for 10 cycles to form 30 s of data, and the subsequently FFT was performed to derive the content ratio. Further, to compare the difference in the EEG data length, the EEG data of 1 s after the short time vibration stimulation was connected for 10 cycles to form 10 s data; thereafter, FFT was performed to derive the content ratio. Finally, the EEG data of only 1 s after the short time vibration stimulation was used as 1 s data, and FFT was performed to derive the content ratio.

Table V shows the verification performance for the 30 s data, Table VI shows the verification performance for the 10 s data, and Table VII shows the data for only 1 s. After

TABLE V
EER WITH SVM USING 30 S DATA [%].

Electrodes	AF3	F7	F3	FC5	T7	P7	O1	O2	P8	T8	FC6	F4	F8	AF4	average
EER	10.7	11.1	12.4	12.7	17.5	8.7	12.2	10.0	12.4	9.7	10.5	13.8	10.9	11.6	11.7

TABLE VI
EER WITH SVM USING 10-S DATA [%].

Electrodes	AF3	F7	F3	FC5	T7	P7	O1	O2	P8	T8	FC6	F4	F8	AF4	average
EER	14.2	12.1	13.1	10.5	19.9	11.4	13.2	10.6	10.8	13.4	15.5	15.9	14.4	14.5	13.5

TABLE VII
EER WITH SVM USING 1 S DATA[%].

Electrodes	AF3	F7	F3	FC5	T7	P7	O1	O2	P8	T8	FC6	F4	F8	AF4	average
EER	29.1	21.8	30.0	23.4	28.3	25.0	20.3	21.0	22.0	24.5	19.8	25.7	23.3	29.1	24.5

comparing the data in Tables 3 and 5, the average EER is observed to have reduced from 24% to 11%, indicating that the introduction of SVM has improved the verification performance. The comparison between Tables V and VI shows the longer data length of 30 s exhibits better verification performance, because the longer data length of EEG used for FFT has higher frequency resolution. However, for certain electrodes, the verification performance was better with 10 s data. This is an interesting phenomenon to be considered further. Tables VI and VII show that the average EER worsened by 11% and the EER also worsened for all electrodes when the data length of EEG is further reduced. In practiced applications, a shorter measuring time is preferred. Verification using 1 s data assumed such a situation.

VII. CONCLUSIONS

We proposed a new method of stimulus presentation that provides a short-time and imperceptible vibration stimulus. After confirming that an evoked response occurs, we evaluated the verification performance and compared it with the verification results of previous studies. As a result, we confirmed that using EEG immediately after a short period of stimulation resulted in higher verification performance than when using continuous stimulation as in the previous study. In addition, we introduced SVM into the verification. As a result ,the average EER was 11%, and the verification performance was further improved. However, this is still not enough.

In this study, we found that for certain electrodes, the results were better with 10 s of data than with 30 s of data. Although the frequency resolution is higher with longer data lengths, the fact that the verification performance is better even with shorter data length may indicate that more salient individual characteristics are obtained rather than a degradation in frequency resolution. Because cross-validation tests were conducted, it is difficult to determine whether the results were due to chance; thus, further detailed examination is necessary. The reason for the deterioration of the verification performance of the 1 s data is thought to be due to the frequency resolution. In addition, 10 s data included the EEGs evoked by 10 stimulus presentations, whereas the 1 s data included only the EEGs evoked by one stimulus presentation. When multiple cycles are processed through FFT, the obtained spectrum has a similar effect with averaging in a frequency domain and it results in more stable spectral features. These differences may have affected the results for the 1 s data. In future, we will study the individual features that are discriminative even when the data length is short. Furthermore, the number of subjects needs to be increased to improve the reliability.

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