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Electroencephalographic feature evaluation for improving personal authentication performance

Jae-Hwan Kang[a], Young Chang Jo[b,*], Sung-Phil Kim[a,*]

[a] Department of Human Factors Engineering, Ulsan National Institute of Science and Technology, Ulsan, Republic of Korea
[b] Human Care System Research Center, Korea Electronics Technology Institute, SeongNam, Republic of Korea

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A B S T R A C T

Electroencephalography (EEG), a method of continuously recording the electrical activity of the brain, provides signals that are among the most promising types of information usable in vital biometrics. However, reliable biometrics based on EEG are still under development since it remains unclear how to extract EEG features that can be used to identify individuals the most effectively. In this study, new EEG features for use in biometrics were proposed and their effectiveness for personal authentication was demonstrated using an open-access EEG database containing 109 personal EEG datasets. From the EEG signals, we extracted 10 single-channel features (seven spectral and three nonlinear) by performing spectral and nonlinear analyses and 10 multichannel features by conducting network analysis based on phase synchronization. A distance-based classifier was built based on the extracted features to distinguish the self from the others. The performance of the proposed personal authentication scheme was assessed in terms of the equal error rate (EER) and false rejection rate (FRR) when the false acceptance rate (FAR) was fixed at 1%. The EER was 0.73% with the eyes open (REO) and 1.80% with the eyes closed (REC), and the FRR with a 1% FAR was 1.10% (REO) and 2.20% (REC). These results are superior to those of previous studies in which the same database was used. In addition, the nonlinear and network features appeared more important than the spectral features for authentication. This method of utilizing EEG features for personal authentication is expected to facilitate the advancement of EEG-based biometric systems.

1. Introduction

With the increasing spread of information in modern society, protecting personal information is becoming more critical. Information systems today therefore should be equipped with reliable means of personal authentication to protect personal information from countless types of imposter attacks. To date, numerous personal authentication systems have been developed for this purpose. Recently, the use in biometrics of signals provided by monitoring the electrical brain activity on the scalp via electroencephalography (EEG) has been proposed [1,2]. Since human EEG signals contain information related not only to specific cognitive processes but also to individual genetic characteristics [3,4], they can be employed in biometrics, compensating for some of the drawbacks of the conventional systems based on static modalities. As such, EEG-based biometric systems have been investigated for decades in numerous studies, which have focused on topics ranging from the development of mobile EEG devices to the implementation of authentication algorithms (see [5,6,7] for comprehensive reviews of recent EEG-based biometric developments).

To develop EEG-based biometrics, it is crucial to determine how to design a task paradigm to acquire EEG features related to personal characteristics. From this perspective, EEG-based biometrics can be broadly classified as utilizing event-related or resting-state paradigms. The biometrics based on event-related paradigms employ the EEG potentials evoked in response to external stimuli. Many related studies have focused on individual differences in the components of event-related potentials (ERPs) in EEG signals evoked by specific cognitive tasks. For instance, visual evoked potentials (VEPs) in response to self- and nonself faces were used in biometrics in one study, and personal authentication with an 86.1% accuracy rate, a 13.9% false acceptance rate (FAR), and a 13.9% false rejection rate (FRR) was achieved [8]. In similar VEP studies, the accuracy was improved to 95% [9] or 98% [10]. Armstrong et al. focused on individual ERP differences during a semantic language memory task and reported accuracies of 82%–97% [11]. Marcel and Millan proposed an EEG biometric based on their previous speaker and face authentication paradigm [12].

* Corresponding authors.
E-mail addresses: ycjo@keti.re.kr (Y.C. Jo), spkim@unist.ac.kr (S.-P. Kim).

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Meanwhile, resting-state EEG signals obtained with the eyes open (REO) or closed (REC) have been employed for personal authentication in other biometric studies. Since no specific behavioral task is involved in this type of paradigm, EEG feature extraction and classification design are of primary interest. For instance, Poulos et al. proposed an algorithm consisting of nonlinear model parameters and vector quantization neural network classifiers to attain correct classification with a 99.5% significance level [13,14]. Other researchers have investigated individualized occipital alpha rhythms (8–12 Hz) associated with resting states, reporting that the alpha power and peak frequency over the occipital regions presented the strongest heritability in EEG signals [4,15]. Accordingly, Paranjape et al. proposed an EEG-based biometric using alpha rhythms during REO and REC, which could reportedly distinguish the self from the others with 85% accuracy [16]. In a recent study, individual EEG templates, called eigenbrains, were developed using principal component analysis (PCA) and multilinear PCA. This method was applied to the resting EEG signals of 30 subjects, resulting in less than 90% accuracy [17].

Furthermore, some open-access EEG databases have been widely adopted in recent EEG-biometrics studies irrespective of the task paradigm to test analytic methods or/and authentication algorithms. In a recent review, Abo-Zahhard introduced a variety of authentication methods using a range of EEG features ranging from evoked potentials to spectral features, which were examined using five public EEG databases [18]. Similarly, del Pozo-Banos et al. investigated the parameters suitable for use in time-frequency analysis for EEG-biometrics by employing six publically available databases [19]. In particular, since the public EEG Motor Movement/Imagery Database (EEGMMIDB) [20] contains information from a large number of participants, it has been employed in three recent EEG-biometric studies to test the efficiencies of the developed feature extraction and personal authentication methods and to evaluate their performances by comparison with the results of other studies [21,22,23]. Specifically, La Rocca et al. utilized the EEGMMIDB to develop a new authentication algorithm based on functional connectivity measures and performed a personal authentication test using a Mahalanobis distance-based classifier combined with fusion algorithms [23]. Their functional connectivity analysis revealed the predominance of the frontal regions (F7 and F8) in personal identification. Fraschini et al. used the same database and proposed employing the eigenvector centrality (EC) of the phase lag index (PLI) from both high beta (20–30 Hz) and gamma (30–50 Hz) bands as features for biometrics [22]. By utilizing the EEG features proposed by both La Rocca et al. and Fraschini et al., Garau et al. developed several types of fusion algorithms involving feature- and score-level fusion to increase the personal authentication performance [21].

In the present study, we also adopted the EEGMMIDB to develop and evaluate a novel personal authentication algorithm. This algorithm includes biometric feature extraction from EEG signals and assessment of those features for personal authentication. To apply the proposed algorithm, we first extracted three types of EEG features, specifically, spectral, nonlinear, and network features, which have been employed as efficient biomarkers of individual sleep, clinical, or genetic characteristics [2,4]. Then, we measured the normalized Euclidean distances in the feature space between the self and others to conduct personal authentication. This analysis also enabled us to evaluate the contribution of each feature to personal authentication. To validate the use of the proposed EEG features and authentication method, the performance of the proposed algorithm was compared to those of the algorithms employed in previous studies that used the same database. In addition, we examined the effects of two key nonlinear parameters, namely, the time delay τ and embedding dimension D, on the personal authentication performances of the nonlinear features.

2. Methods and materials

2.1. Data preparation

To develop an algorithm for EEG-based biometrics, we utilized the EEGMMIDB [20], which is publicly accessible on the PhysioNet website [24]. Since this database was originally designed to support brain–computer interface research, the EEG signals were recorded in 14 individual runs per person, where the first two runs consisted of 1 min resting state with eyes open (REO) and eyes closed (REC) periods, and the remaining 12 runs consisted of four different types of motor imagery tasks with three repetitions of each type. In the EEGMMIDB, the 64-channel EEG signals were acquired at a 500 Hz sampling rate from 109 subjects in accordance with the international 10–20 system. The detailed information about this database is provided in [20]. As in the other studies in which this database was used, we employed only the first two 1-min-long runs of EEG data, which were recorded during REO and REC. We also used only 56 EEG channels out of 64, eliminating the eight channels (AF7/8, FT7/8, T9/10, Oz, Iz) that were excluded in the previous studies [21,23].

2.2. EEG preprocessing

We first down-sampled the EEG signals from 500 Hz to 200 Hz to reduce the computational resource requirements. The raw signals were band-pass filtered using a finite impulse response (FIR) filter with a pass band of 2–55 Hz to increase the signal-to-noise ratio. In the first procedure, the filtered EEG signals corresponding to the REC and REO periods were segmented into five disjoint 12 s epochs for the subsequent spectral and nonlinear analyses. In the second procedure, the raw EEG signals were passed through five band-pass FIR filters, each generating five individual rhythms oscillating in the theta (θ, 4–8 Hz), alpha (α, 8–13 Hz), low beta (Lβ, 13–20 Hz), high beta (Hβ, 20–30 Hz), or gamma (γ, $30-40$ Hz) frequency bands. Then, the individual EEG rhythms were again segmented into five 12-s epochs for the subsequent network analysis. The spectral and nonlinear analyses were conducted for each channel independently and thus are collectively referred to as single-channel analysis hereafter, whereas the network analysis was conducted across multiple channels and thus is referred to as multi-channel analysis hereafter.

2.3. EEG channel selection for personal authentication

Prior to the main EEG processing for personal authentication, we conducted a preliminary test to investigate specific brain regions in which useful EEG features could be found for self-identification. Indeed, EEG features useful for personal authentication should satisfy consistency in the same recording trials of a person in parallel with self-distinctness from others. Therefore, we took two main factors into account that were likely to result in poor authentication performance due to large variations of EEG features within intra-person trials. The first factor was EOG interference caused by eye movements in the REO condition. It is well known that EOG interference is one of the strongest noise sources in EEG and possible to cause a high variation in EEG features within intra-person trials due to subject's spontaneous eye movements. The second factor was related to special characteristics of enhanced alpha activity in the REC condition. During the REC condition, higher alpha activities were apparently presented across most (especially posterior) brain regions. However, EEG alpha activity in the REC condition temporally appeared and disappeared. Thus, we assumed that EOG interference in the REO as well as the bursting alpha activity in the REC could lead to poor authentication.