Evaluation of a Method of Removing Head Movement Artifact from EEG by Independent Component Analysis and Filtering

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Abstract
Artifacts that contaminate electroencephalography (EEG) signals make it difficult to analyze EEG. The aim of this study was to remove artifacts on EEG, especially those caused by motion, to measure EEG in unconstrained situations. In a previous study, head movements were detected by an accelerometer, and motion artifact components were separated from the recorded EEG by independent component analysis (ICA). This method is effective for reducing the effect of artifacts, but has a risk that EEG components are also removed. In this paper, we introduce an improved artifact removal method based on ICA and filtering. EEG were decomposed by ICA, and a Pearson’s correlation coefficient was calculated between each independent component and each hybrid accelerometer value to distinguish artifact components. Artifact components were then high-pass filtered. In this study, subjects were instructed to move their heads randomly, while keeping their eyes closed. The previous method was adapted using 1, 2, 3, 5 and 10 s to find the most suitable epoch to minimize the mean absolute amplitude of the cleaned EEG. Then, using this epoch, the proposed method was compared with the previous method by frequency analysis. Low frequency power (0.1–3 Hz) was normalized to unity because most power caused by motion artifacts exists in the low power band. If the normalized theta (4–8 Hz), alpha (8–13 Hz) and beta (13–40 Hz) powers of cleaned EEG are higher than that of raw EEG, this indicates that the effect of motion artifacts is small and EEG components are retained. The results obtained from theta and alpha power comparison showed that the proposed method performed better than the previous method. This result suggests that the proposed artifact removal method is more effective to reduce the effect of artifacts while retaining the EEG components.

Keywords: artifact removal, independent component analysis, filtering, accelerometer, EEG.

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1. Introduction
Elucidation of brain function has been the recent focus of many researchers. Above all, EEG is used for analyzing brain activity. There are two ways to measure EEG. One is an invasive method that records intracranial EEG with high precision. However, this method has inherent risks of damaging brain tissues due to the need to place electrodes by surgery. The other method is noninvasive, in which electrodes are placed on the scalp to record EEG in a straightforward manner. However, artifacts often mingle with EEG, which makes it difficult to analyze intrinsic signals from the brain. Therefore, the subject is preferably restrained during EEG recording, because head or body movements cause significant artifacts on the recorded EEG.

The aim of this study was to remove motion artifacts from recorded EEG while keeping the loss of EEG information to a minimum. If motion artifacts can be removed, the method could be clinically applied to measure EEG in children with attention deficit hyperactivity disorder or cerebral palsy, who exhibit many head movements [1]. In addition, EEG can be measured essentially in unconstrained situations.

In a previous study, motion artifact components in EEG containing artifacts were separated by independent component analysis (ICA) [2]. In this method, head movement is recorded by an accelerometer placed on the head, with the assumption that EMG and other artifacts generated by head movement correlate with the head accelerometer data. Using the accelerometer data, artifact components are detected and removed. This method has the merit that it does not depend on pre-learned data. Additionally, this method is effective in reducing artifacts, but has the risk of removing EEG components by mistake; independent components (ICs) that are removed as artifact components may also contain EEG components.

To solve this problem, we introduce an improved artifact removal method based on ICA and filtering. ICs containing artifacts are high-pass filtered instead of removed. This is because most power derived from motion artifacts exist in the low power band (0.1–3 Hz). Moreover, a hybrid accelerometer is used to record also the angular velocity as head movement. To validate the proposed method, we compared this method with the previous one.

2. Methods
2.1 Subjects
Six healthy adult males (aged 21–24 years, right handed) participated in this study. All subjects provided written informed consent before the experiment. We obtained approval for all measurements conducted from the ethics committee of the Faculty of
Table 1  Artifact generation protocol. One set is shown. All subjects performed two sets with eyes closed.

| Task                | Duration [s] |
|---------------------|--------------|
| Resting             | 10           |
| Random movement     | 30           |
| Resting             | 10           |
| Random movement     | 30           |
| Resting             | 10           |
| Random movement     | 30           |
| Resting             | 10           |

2.2 Signal measurement

EEG was recorded from 16 channels using active electrodes. The following channels were used: Fp1, Fp2, F3, F4, Fz, T7, T8, C3, C4, Cz, P3, P4, Pz, PO7, PO8, and Oz (the extended 10–20 system). The reference electrode was placed on A2, and the ground electrode was placed on AFz. Then, a gUSBamp (g.tec, Austria) was used to record EEG. The sampling rate was set at 512 Hz. Impedance was maintained below 5 kΩ.

To measure head movement, a hybrid accelerometer WWA-010 (wireless-T, Japan) was set at position FCz. This sensor is able to record 3-axis acceleration and 3-axis angular velocity using ADXL345BCCZ (Analog Devices, Japan) and ITG-3200 (InvenSense, Japan) inside the sensor. The data of the hybrid accelerometer were recorded using an AccelViewerHybrid II (wireless-T, Japan). The sampling rate of the sensor was set at 50 Hz.

2.3 Experimental task

Subjects performed “random movement” and “resting” tasks while closing their eyes to prevent eye blink artifacts during the random movement task. “Random movement” is defined as movement of the head in arbitrary directions and pace while sitting. All subjects were instructed before the experiment not to move their facial muscles. Artifact generation protocol is described in detail in Table 1. One set of task consisted of 10 s of “resting” and 30 s of “random movement” repeated three times. The aim was to generate non-artifact EEG and artifact-contaminated EEG. Each subject performed two sets of the protocol to collect six data samples of 30-s EEG contaminated by head movement artifacts.

2.4 Signal processing

First, recorded EEG signals were band-pass filtered in the range 0.1–50 Hz with a fourth-order Butterworth filter. Next, the data of the hybrid accelerometer were resampled at 512 Hz. EEG power spectra were calculated by FFT using 30-s windows of EEG data. MATLAB R2012b (Mathworks, USA) was used for signal processing.

2.5 Removal method

First, recorded EEG were divided into epochs of a few seconds, and the parts of the EEG in which artifacts mingled were detected. The amplitude of a non-artifact EEG is <100 µV [3]. Therefore, the mean absolute amplitude of EEG was used so as to decide if artifacts mingled with EEG. When this value was <20 µV, the following procedures were skipped.

Next, EEG containing artifacts were decomposed into ICs by ICA. ICA is a blind source separation method. Observed signals (x1, x2, ..., xn) are assumed to be linear combinations of unknown source signals (s1, s2, ..., sm):

\[ x = A \times s. \] (1)

A is a mixing matrix. A separate matrix W is calculated from observed signals to estimate source signals, s:

\[ s' = W \times x. \] (2)

After performing ICA, Pearson’s correlation coefficient was calculated between each IC and hybrid accelerometer measurement except z-axis acceleration. The reason is that the z-axis was in the vertical direction (Fig. 1), so that z-axis acceleration did not measure head movement in this study. Pearson’s correlation coefficient is a statistical index r, calculated by the following formula:

\[ r = \frac{\sum_{i=1}^{m} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{m} (x_i - \bar{x})^2 \sum_{i=1}^{m} (y_i - \bar{y})^2}}. \] (3)

Each ICs was substituted for x, and each hybrid accelerometer values was substituted for y, and \( \bar{x} \) and \( \bar{y} \) were mean values. The threshold was set at two standard deviations of the index r. ICs that were above the threshold and had the highest correlation with one or more hybrid accelerometer values were identified as an artifact component (Fig. 2).

In the previous study [2], the ICs identified as artifacts were removed. In the proposed method, however, the identified ICs were high-pass filtered with a fourth-order Butterworth filter, because head movement artifacts exist in the low power band [2, 4]. The power of most identified ICs was higher than that of non-identified ICs (below 3 Hz). Therefore, the cutoff frequency was 3 Hz. Finally, artifact-reduced EEG were reconstructed using the filtered ICs and non-filtered ICs with mean amplitude <20 µV.
For comparative analysis, the previous method hereinafter refers to the procedures of removing artifacts without using high-pass filtration.

To determine the optimal epoch length to use for the previous method, epochs of 1, 2, 3, 5 and 10 s were segmented from recorded EEG signals and processed by the previous method to decide which epoch length is most suitable to minimize the EEG amplitude of the cleaned EEG, for each subject and each trial. The mean absolute amplitudes of raw and cleaned EEG were compared for each epoch, and the epoch that yields the smallest amplitude in the cleaned EEG was chosen (Table 2).

3. Validation

Frequency analysis was performed to compare the previous and the proposed methods. When EEG amplitude is reduced by the artifact removal process based on ICA, the overall frequency power spectra decrease. Therefore, the frequency power components were normalized by the low frequency power (0.1–3 Hz) which was assigned a value of 1, because most power components caused by motion artifacts exist in this low power band. If the normalized theta (4–8 Hz), alpha (8–13 Hz) and beta (13–40 Hz) powers of cleaned EEG are higher than the power of normalized components of the raw EEG, this indicates that the effect of motion artifacts is small and EEG components are retained. Especially, alpha waves appear strongly at the posterior channels during closing of the eyes [5]. In fact, we confirmed that the frequency power of alpha waves was recorded more frequently at the posterior channels (P3, P4, Pz, PO7, PO8, and Oz) than at other channels in resting EEG for all subjects. Hence alpha waves are useful to indicate whether EEG components are removed by mistake. The power band of raw EEG and those of cleaned EEGs obtained by the previous and the proposed methods were compared. MATLAB2010b Statistical Toolbox (Mathworks, USA) was used to validate whether or not there was a significant difference using a paired t-test.

4. Results

Figure 2 shows an example of an IC identified as artifact. The blue line represents the identified IC, the red line the filtered IC, and the black line the y-axis angular velocity. Each value was normalized for ease of comparison. The correlation coefficient between the identified IC and y-axis angular velocity was −0.6565, which is a strong correlation. Using the previous method, the identified ICs were removed. Conversely, in the proposed method, the identified ICs were high-pass filtered to retain EEG components contained in the identified ICs.

Table 2 The most suitable epoch time length (1, 2, 3, 5 or 10 s) that minimizes the mean absolute amplitude of cleaned EEG by the previous method for each subject and each trial.

| Trial number | Subject number |
|--------------|----------------|
| Trial number | Subject number |
| 1            | Subject number |
| 2            | Subject number |
| 3            | Subject number |
| 4            | Subject number |
| 5            | Subject number |
| 6            | Subject number |

![Flowchart of the proposed method](image)

For comparative analysis, "the previous method" hereinafter refers to the procedures of removing artifacts without using high-pass filtration.

To determine the optimal epoch length to use for the previous method, epochs of 1, 2, 3, 5 and 10 s were segmented from recorded EEG signals and processed by the previous method. The epoch was selected using the obvious method to decide which epoch length is most suitable to minimize the EEG amplitude of the cleaned EEG, for each subject and each trial. The mean absolute amplitudes of raw and cleaned EEG were compared for each epoch, and the epoch that yields the smallest amplitude in the cleaned EEG was chosen (Table 2).

**Table 2** shows the most suitable epoch to decrease the amplitude of EEG amplitude. The epoch was selected using the previously mentioned method.
mean absolute amplitude of cleaned EEG obtained by the previous method, as explained above. Table 3 shows the average number of ICs identified as artifact in each subject and trial. The maximum number is 3.67, and the minimum is 0.80. With the previous method, these identified ICs were removed. In contrast, in the proposed method, such ICs were high-pass filtered.

To validate the alpha power band, EEG recorded on posterior channels were analyzed. Figure 4 shows an example of raw EEG (a), cleaned EEG obtained by the previous method (b), and cleaned EEG obtained by the proposed method (c). Each 90 to 120-s EEG segment is the average EEG for the posterior channels (P3, P4, Pz, PO7, PO8, Oz) for subject 4 in the first trial of artifact generation protocol. The 105 to 108-s segment containing an IC identified as artifact is shown in Fig. 2.

Table 3: Average number of ICs identified as artifact by the proposed method.

| Trial number | Subject number | 1  | 2  | 3  | 4  | 5  | 6  |
|--------------|----------------|----|----|----|----|----|----|
| 1            |                | 2.33| 2.20| 2.73| 2.80| 3.33| 2.60|
| 2            |                | 3.00| 3.33| 2.20| 3.00| 2.90| 1.50|
| 3            |                | 3.33| 2.60| 3.00| 3.00| 2.73| 2.00|
| 4            |                | 3.50| 2.20| 2.73| 3.40| 3.67| 2.00|
| 5            |                | 2.27| 2.83| 1.67| 3.67| 2.80| 0.80|
| 6            |                | 3.00| 3.33| 2.70| 3.00| 3.33| 1.67|

The epoch length for each subject and trial are shown in Table 2.

mean absolute amplitude of cleaned EEG obtained by the previous method, as explained above.

Table 3 shows the average number of ICs identified as artifact in each subject and trial. The maximum number is 3.67, and the minimum is 0.80. With the previous method, these identified ICs were removed. In contrast, in the proposed method, such ICs were high-pass filtered.

To validate the alpha power band, EEG recorded on posterior channels were analyzed. Figure 4 shows an example of raw EEG (a), cleaned EEG obtained by the previous method (b), and cleaned EEG obtained by the proposed method (c). This figure shows 90–120 s of an EEG of subject 4 in the first trial of the artifact generation protocol. The mean absolute amplitude of raw EEG, cleaned EEG by the previous method, and cleaned EEG by the proposed method were 39.5 μV, 17.4 μV, and 17.9 μV, respectively. Figure 2 is an example of an IC that was identified as artifact from 105 to 108 s.

Figure 5 shows a comparison of the normalized theta (a), alpha (b), and beta (c) powers of raw EEG and cleaned EEGs using the previous and the proposed methods for each subject, and the mean value of all subjects. In the comparison of theta power (a), significant differences (Raw EEG vs Previous method, Raw EEG vs Proposed method, Previous method vs Proposed method) were found in all subjects except subject 6. The mean normalized theta powers of raw EEG, cleaned EEG by the previous method, and cleaned EEG by the proposed method were 0.010, 0.023, and 0.038, respectively. In the comparison of normalized alpha power (b), significant differences (Raw EEG vs Proposed method, Raw EEG vs Proposed method) were found in all subjects except subjects 4 and 6. Significant differences between the two methods were also observed in subjects 1 and 4, as well as mean value of all subjects. The mean normalized alpha powers of raw EEG, cleaned EEG by the previous method, and cleaned EEG by the proposed method were 0.022, 0.036, and 0.041, respectively. In the comparison of beta power (c), few significant differences between the previous and the proposed methods were observed. The mean normalized beta powers of raw EEG, cleaned EEG by the previous method, and cleaned EEG by the proposed method were 0.0051, 0.0092, and 0.0089, respectively.

5. Discussion

Figure 2 confirms that ICA is capable of separating artifact components and that the hybrid accelerometer is able to detect those components. In the previous study, ICs identified as artifact were removed along with EEG components. The filtered IC suggests that the proposed method is able to retain EEG components.

Using the mean absolute amplitude of EEG, the most suitable epoch length to separate artifacts was selected (Table 2). The data reflect the fact that subjects moved their head in a random direction and pace, so that the epoch length was different in each trial of “random movement”. Moreover, Table 2 suggests that it is necessary to reserve at least one 2-s epoch to separate artifact components.

Table 3 shows the mean number of ICs identified as artifact in each trial. The previous method identified a small number of such ICs. Despite the small number, since all ICs identified as artifacts are removed, there is a risk that EEG components are removed by mistake. However, using the proposed method, this
risk is reduced.

Figure 4 shows an example of raw EEG (a), cleaned EEG obtained by the previous method (b) and cleaned EEG obtained by the proposed method (c). The figure shows 90–120 s of EEG recording of subject 4 in the first trial of the artifact generation protocol. The mean absolute amplitude of cleaned EEG by the previous method was 22.1 μV lower, and that by the previous method was 21.6 μV lower compared to raw EEG. Figure 4 indicates that both methods reduce EEG amplitude. From this result, the effect of artifact is reduced by both methods.

Figure 5(a) suggests the advantage of the proposed method in reducing the effect of motion artifacts, because the normalized theta power of cleaned EEG by the proposed method is retained to a greater extent compared to the previous method. In the comparison of alpha power (b), significant differences (Raw EEG vs Previous method, Raw EEG vs Proposed method) were observed in all subjects except subjects 4 and 6. In subjects 4 and 6, it is possible that the recorded EEG was contaminated by other artifacts such as neck EMG uncorrelated with head movement, eye movement, or myographic artifact caused by biting on the teeth, more than in other subjects. In addition, if this temporal muscle EMG contaminates the reference channel (A2), all channels would be affected, and it becomes difficult to separate motion artifact components from recorded EEG in these subjects. To investigate these causes, we will have to revise the testing procedure to include other movements such as neck EMG and eye movement. Moreover, we have to caution subject not to bite on his/her teeth. However, the alpha power of cleaned EEG obtained by the proposed method was significant higher than that by the previous method in subject 1 and 4 as well as mean of all subjects. This result suggests that the proposed method is able to reduce the effect of artifact while retaining EEG components. On the other hand, Figure 5(c) suggests that the proposed method retains the same normalized beta power as the previous method.

6. Conclusion

In this study, using the mean absolute amplitude of EEG as an artifact index, the most suitable epoch time length to separate artifact components by ICA was found. Next, motion artifact components were detected using hybrid accelerometer data. Then, the artifact ICs were filtered by the proposed method and the cleaned EEG were compared with those obtained by the previous method. To compare the two methods, frequency analysis was performed on the processed EEG data. As a result of evaluating theta and alpha power, the cleaned EEG obtained by the proposed method retained higher EEG power than the cleaned EEG obtained by the previous method. These results suggest that the proposed method is able to reduce the effect of artifacts while retaining EEG components. In the future, to reduce the influence of other artifacts, it is necessary to caution subject not to bite his/her teeth and measure other movements including EMG and eye movement.

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Disclosure

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