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Original Article

Feasibility of the Application of Moment Of Inertia as a Feature to Study High-Frequency Bands in Brain Signals

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Abstract

Introduction
Many features, emerging from mathematical techniques, have been used in the analysis of brain signals. In this study, the physical quantity of "moment of inertia" (MOI) was introduced as a feature to enhance high-frequency waves (HFWs) in electroencephalography (EEG).
Materials and Methods
In this research, the recorded EEGs from F3, F4, and Cz points in 20 males were used. A total of 30 noiseless epochs (4 sec with a 1 sec overlap) were selected for each eyes-open and eyes-closed state from each brain signal. After averaging the relative power spectrum (RPS) of 30 epochs and obtaining an RPS with low fluctuation, the MOIs of the power spectrum and each EEG band were calculated.
Results
The MOI enhanced the HFWs of brain signals; therefore, HFW fluctuations in the power spectrum of MOI were more evaluable and observable than those of RPS. Paired t-test showed no significant difference in the asymmetry of MOI between the eyes-open and eyes-closed states (P=0.227), while the MOIs of alpha and beta bands between these two states were significantly different [F(1, 38)=11.8; P=0.001 and F(1, 38)=12.9; P=0.001, respectively].
Conclusion
This study demonstrated that the MOI of different frequency bands might be used as a feature for some patients who are different from healthy subjects in terms of high-frequency bands or performance of two hemispheres. Therefore, in order to ensure the applicability of the obtained results, evaluation of MOI for EEG of some disorders, such as attention-deficit hyperactivity disorder, alcoholism, and autism is suggested in future studies.

Keywords: Beta Rhythm, Brain Waves, Digital Signal Processing, Asymmetry

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1. Introduction

Since the introduction of digital electroencephalography (EEG), quantitative analysis of brain signals has rapidly improved. Researchers have studied brain waves through applying the features of mathematical techniques, including Fourier transform [1], wavelet analysis [2], and correlation [3]. Even concepts of physical quantity, such as entropy [4], chaos theory [5], and fractal theory [6] have been applied.

The introduced methods attempt to trace the differences between each person's moods or even diseases, associated with psychological and psychiatric domains through determining the probable changes in brain signals, based on some of the reviewed features [7]. While the applied concepts, such as entropy, energy, power, and chaos, may lose their actual physical meaning, an index or feature can be equally valuable for differentiating the patients' EEGs from those of healthy individuals.

Today, EEG is commonly used to help distinguish psychological diseases and track the improvement process [1]. Furthermore, in neurofeedback training, attempts have been made at suppressing or enhancing some of the frequency bands in certain areas of the brain to treat some symptoms, including depression and attention-deficit hyperactivity disorder (ADHD) [8-10].

The ability to detect the differences in some brain signal bands in patients compared to healthy people is very important for the therapist in terms of both disease diagnosis and treatment. A common technique to extract the frequency bands of EEG is fast Fourier transform (FFT), which plots the power spectrum of the recorded signals [11]. For instance, children with ADHD have some differences in high-frequency waves (HFWs), recorded from the sensorimotor area of the brain (central region), compared to healthy children; this issue can be corrected by neurofeedback training [12, 13].

The amplitude of theta [14] and beta bands in alcoholics is greater than non-alcoholics. This increase is observed in the beta band in all men, especially in the central region of the head [15]. The difference in beta bands in the eyes-closed state can be used as a feature for distinguishing alcoholics from the non-alcoholics. Even some external stimuli, such as extremely-low-frequency magnetic fields, can change the amplitude of HFWs in the EEG, recorded from their radiation [16-18].

Nevertheless, the important issue is that HFWs in EEG have low amplitudes. Therefore, the study of visual and quantitative variations in high-frequency bands between healthy subjects and patients becomes difficult with regard to individual differences (e.g., skull thickness and skin conductance). Even the use of relative power instead of absolute power does not solve this problem [11].

If the HFW amplitude of brain signals is increased in the recorded EEG by using a specific technique, the differences could be better scrutinized. In the present study, the physical quantity of "moment of inertia" (MOI) was introduced as a feature to enhance the HFWs in EEG, recorded from different parts of the scalp. Also, the MOI of various bands was suggested as a useful feature in the study of high-frequency bands.

2. Materials and Methods

2.1. Hypothesis

MOI is widely used in physics for continuous objects, as defined in Equation (1), where m and r denote mass and distance, respectively. If the system includes a set of particles with different masses and distances (discrete system), Equation (1) can be rewritten as Equation (2). Here, m_i is the mass of each particle, and r_i is its distance from the origin [19]. This concept was first developed by Leonhard Euler in 1765:

$$I_p = \int r^2 dm \quad (1)$$

$$I_p = \sum_{i=0}^{n} m_i r_i^2 \quad (2)$$

To calculate the MOI from the recorded EEG, first, the relative power spectrum (RPS) of brain signals was obtained by FFT and plotted; then, MOI was calculated based on Equation (2). However, Equation (2) in the frequency space was rewritten as Equation (3). In this

equation, f_i is the frequency and R_i is denotes its corresponding amplitude in the power spectrum. The frequency space is discrete due to FFT for small segments of the recorded signal; therefore, the frequency resolution would be the reverse of the time length segment [11]:

$$I_p = \sum_{i=0}^{n} R_i f_i^2 \quad (3)$$

Application of Equation (3) to brain signals increases the weight of HFWs due to multiplying frequency square; in other words, MOI reinforces the beta band more than the theta band in EEG. The areas under RPS curves are the same as those in which EEG was recorded [11]. However, the MOI of brain signals for different points varies due to differences in the share of different bands and high-frequency wave boost. In addition to total MOI, the MOI of different bands could be obtained separately and the bands could be compared with each other after calculating and plotting the MOI spectrum.

2.2. *Evaluation of the hypothesis*

2.2.1. Subjects and brain signals

We used the EEGs of 20 males with the mean age of 25.6±1.6 years, which had been recorded in previous research [20, 21]. The participants whose EEGs were studied were right-handed and did not have a positive history of epilepsy, chronic pain, or psychological disorders, leading to long-term medication use. Also, none of the subjects had a prior history of alcohol drinking or tobacco smoking. Each participant had abstained from drinking coffee or tea for at least three hours before the recording sessions. The records of EEG (Thought Technology, Montreal, Canada) results from F3, F4, and Cz points (10–20 system) used in this research were referenced to each participant's ears (unipolar measurement), with the ground placed on the forehead. The data acquisition sampling rate was 992 Hz, and band-pass filtration was performed from 2 to 50 Hz with a 50 Hz notch filter.

2.2.2. Data analysis

We generated the baseline EEG for each participant, in which the recording protocol was 2 min eyes-open and 2 min eyes-closed. After removing the noisy area of each EEG (eye-blinking and electromyography artifacts), 30 noiseless epochs were selected for each eyes-open and eyes-closed state. The epoch length was 4 sec with a 1 sec overlap. The frequency analysis of EEG was subsequently carried out, using FFT with a Hanning filter [11].

After averaging the power spectra of 30 epochs and obtaining a power spectrum with low fluctuation, the contribution of each EEG band and its relative power spectrum were extracted. Next, MOI was calculated based on Equation (3). Consequently, the MOI of each EEG band could be calculated (Figure 1). The analyzed frequency bands included delta (2.5–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), beta (13–30Hz), and gamma (30–47.5 Hz). Furthermore, beta-1 (13–20 Hz) and beta-2 (20–30 Hz) bands were evaluated, owing to their importance in psychology.

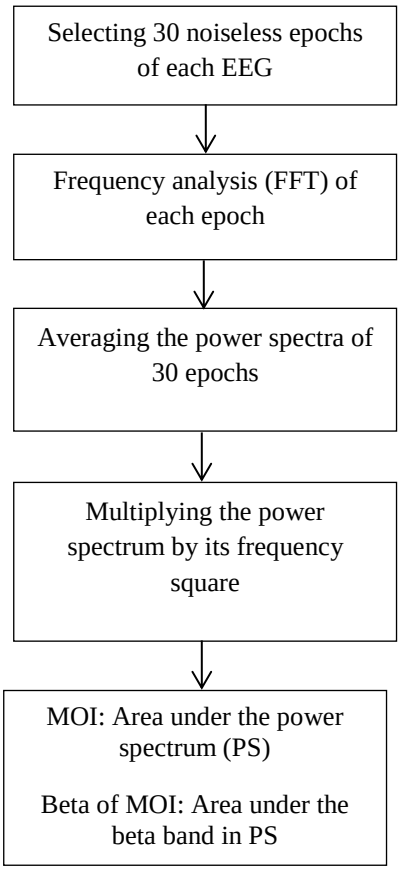

Figure 1. The flow diagram of electroencephalography (EEG) analysis. The stages were carried out separately for the eyes-open and eyes-closed states.

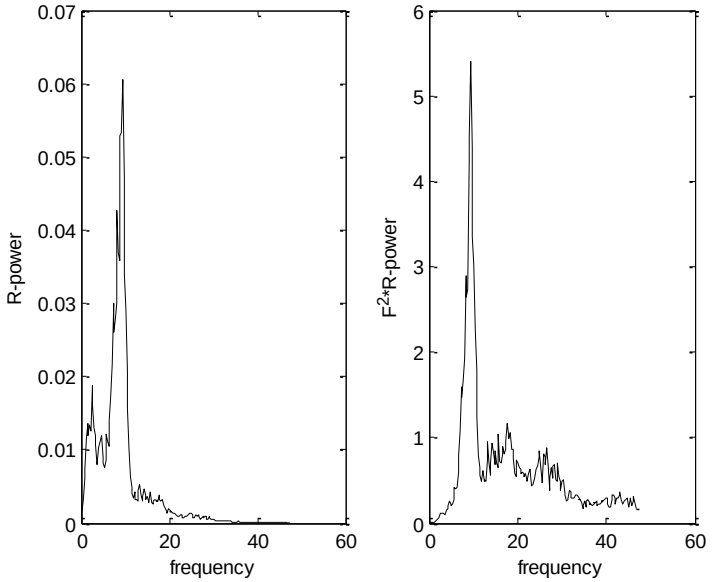

Figure 2. The relative power spectrum (RPS) and power spectrum of the moment of inertia (MOI) of F3 area in one participant drawn in the eyes-closed state

Generally, a frequency above 13 Hz in brain waves is known as HFW. The mentioned processing was performed, using MATLAB-2009a software (MathWorks, Natick, MA, USA). In addition, a feature usually evaluated in the analysis of brain signals is asymmetry, defined as (L-R)/(L+R) [11]. This feature can be calculated for different bands, especially the alpha band [22, 23] and is used mostly for people whose brain activity in the left hemisphere with respect to the right hemisphere may be different compared to healthy subjects [1]. The asymmetries based on MOI were evaluated between the eyes-open and eyes-closed states in all bands.

2.2.3. Statistical analysis

In order to study MOI, the values of MOI for the eyes-open and eyes-closed states were compared, using repeated measures ANOVA at a significance level of 0.05. Repeated measures ANOVA were also used to compare the MOIs of different bands. The MOI asymmetry of EEG signals in the eyes-open and eyes-closed states was compared, using paired t-test at a significance level of $P<0.05$.

3. Results

The RPS and power spectrum of the MOI of F3 point in one participant were drawn in the eyes-closed state (Figure 2). Fluctuations of HFWs in the power spectrum of MOI could be clearly observed, while fluctuations in RPS were not so obvious due to the low amplitude of HFWs. The mean MOIs in the F3, F4, and Cz areas of 20 participants in the eyes-open and eyes-closed states are presented in Figure 3.

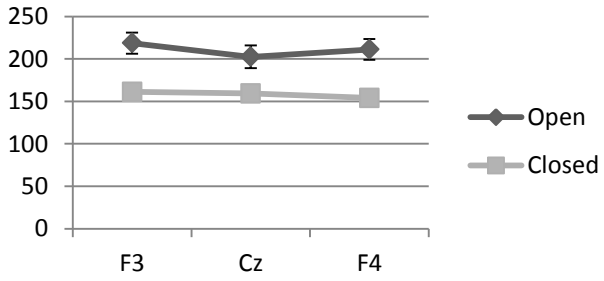

Figure 3. The moment of inertia (MOI) of 20 participants in the F3, F4, and Cz areas in the eyes-open and eyes-closed states

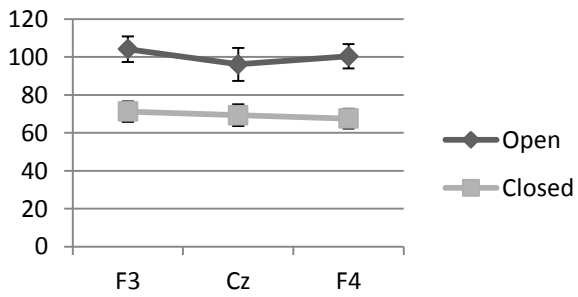

Figure 4. The moment of inertia (MOI) of the beta band in F3, F4, and Cz areas in the eyes-open and eyes-closed states

The repeated measures ANOVA of MOI showed no significant difference among F3, F4, and Cz areas in the eyes-open or eyes-closed state. However, the comparison between the eyes-open and eyes-closed states revealed a significant difference [F(1, 38)=17.6; P=0.000]; these differences are clearly visible in Figure 4. The MOIs of alpha and beta bands between the eyes-open and eyes-closed states were significantly different [F(1, 38)=11.8; P=0.001 and F(1, 38)=12.9; P=0.001, respectively]. The beta band MOI in the eyes-open state was greater than the eyes-closed state (Figure 4); however, the opposite was observed in the alpha band (Figure 5).

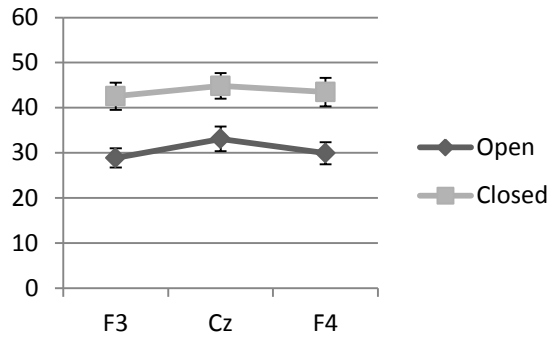

Figure 5. The moment of inertia (MOI) of alpha band in F3, F4, and Cz areas in the eyes-open and eyes-closed states

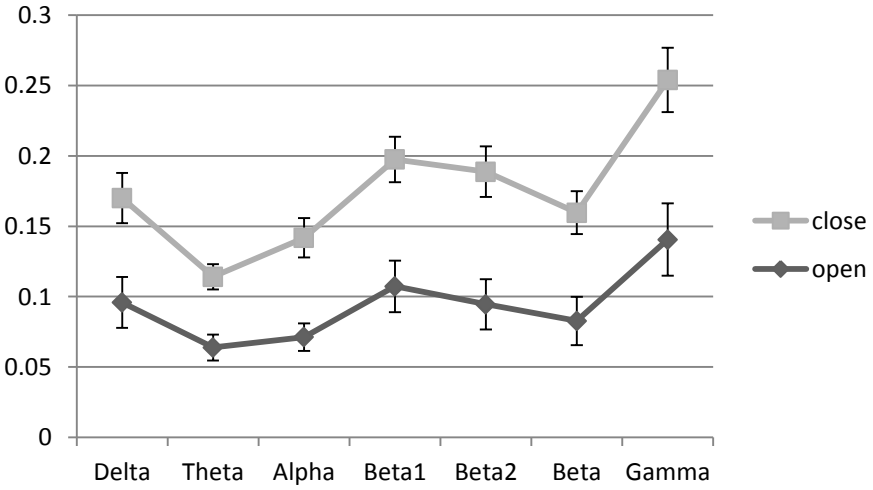

Figure 6. The asymmetry of all bands extracted from the relative power spectrum (RPS) in the eyes-open and eyes-closed states; all the bands showed significant differences (P<0.05).

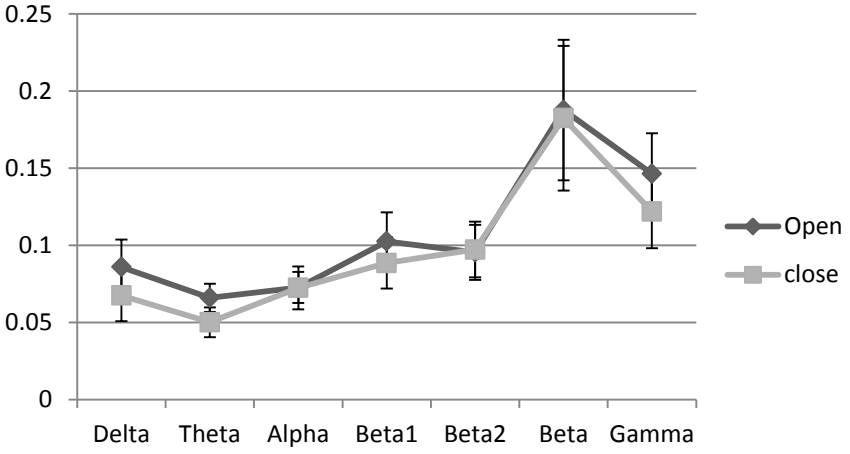

Figure 7. The asymmetry of all bands extracted from the power spectrum of moment of inertia (MOI) in the eyes-open and eyes-closed states. There were no significant differences in any of the bands (P>0.05).

Asymmetry in the eyes-open and eyes-closed states was calculated separately for all the bands extracted from RPS and the power spectrum of MOI (Figures 6 & 7). Paired t-test showed no significant difference in the asymmetry of MOI between the eyes-open and eyes-closed states (P=0.227). At this stage, instead of a particular band, the MOIs of F3 and F4 points were compared.

4. Discussion

As expected, in the present study, MOI enhanced the HFWs of brain signals. Therefore, fluctuations of HFWs in the power spectrum of MOI were more evaluable and observable than RPS (Figure 2). Due to the low weight of low-frequency waves in the recorded EEG, fluctuations in low-frequency waves in the power spectrum of MOI were almost eliminated. Consequently, delta and theta bands of all areas in the power spectrum of MOI were visually quite useless and fluctuations were quite smooth. In contrast, high-frequency fluctuations were bolded, similar to the edges reinforced in digital image processing, where high-pass filters are used to enhance the contrast and low-pass filters are used for smoothing [24].

The spectrum of MOI may be useable for patients who have different HFWs in some areas of the brain compared to healthy people. For instance, in a previous study, absolute beta power, especially 20.5–28 Hz frequencies in the frontal region, changed in male alcoholics [15]. There are abnormalities in neural connectivity in children with autism spectrum disorder. The increased beta activity in the eyes-closed state is assumed to reflect difficulties in motor and sensorial regulation [25]. Also, patients with epilepsy [26] may be able to monitor the seizures automatically without requiring visual monitoring [27, 28], while this is normally accomplished by EEG monitoring [29-31].

As can be seen in Figure 3, MOIs in all the evaluated areas were significantly higher in the eyes-open state compared to the eyes-closed state [inter-group comparison via repeated measures ANOVA; F(1, 38)=17.6; P=0.000], while the analysis of MOI via repeated measures ANOVA showed no significant difference among F3, F4, and Cz areas in either the eyes-open [F(2, 38)=0.933; P=0.402] or eyes-closed [F(2, 38)=0.860; P=0.431] state.

When the eyes are closed, HFW amplitude decreases and the contribution of low-frequency bands in EEG increases with respect to the eyes-open state in all areas of the scalp [11]; such changes and their trends are well illustrated by MOI. In other words, if the MOIs of the same bands are compared in these two states, the MOI of the beta band in the eyes-closed state will be smaller than that of the eyes-open state in the recorded signals (Figure 4), while the opposite is true for the alpha band (Figure 5).

The high amplitude of beta rhythms in the eyes-open state can be considered as a result of desynchronization in neuronal networks [11]; this issue is shown correctly by the MOI of different bands. Therefore, in cases where some of the activities or symptoms cause amplitude changes in high- and low-frequency waves, MOI can be an appropriate feature for monitoring. For instance, in studies on ADHD children at rest in the eyes-open and eyes-closed states, differences have been observed in comparison with normal controls, such as an increase in theta and a decrease in both alpha and beta bands [32, 33]. Also, sometimes, greater absolute beta power and smaller relative alpha-1 and beta power are observed [32].

Evaluation of quantitative EEG (QEEG) in children with autism disorders demonstrated some abnormalities in the connectivity of temporal lobes with other lobes in the gamma frequency band (36–44 Hz) [34] and indicated increased delta-theta activity in the frontal region [35]. Begic et al. compared QEEG findings in patients with "positive" schizophrenia, "negative" schizophrenia, and depression. They reported an increase in delta activity in the frontal region in "positive"

schizophrenia, while a decline was reported in beta activity in the negative type [36].

Also, Jeong et al. reported that adjustment disorder due to major depressive disorder could be distinguished by the absolute power of alpha and high beta bands [37]. On the other hand, a change in the absolute bands could be seen in a symptom in comparison to the control group, whereas no significant difference was observed in the relative bands or vice versa; in fact, this is not a very favorable issue in the power spectrum analysis of patients.

The amplitude of EEG recorded in a particular subject depends on many factors (neurophysiological, anatomical, and physical properties of the brain and the surrounding tissues), which vary from one subject to another and are basically unknown. These disparities result in large variations in the absolute EEG spectra. To compensate for these variations and to reduce the changeability of absolute power, the relative EEG power is sometimes computed [11].

Accordingly, relative power differences between patients and healthy subjects are expected to deliver better results than absolute power, while in many cases, the opposite is true. For instance, in a previous study, patients with juvenile myoclonic epilepsy showed increased absolute power of delta, alpha, and beta bands, while QEEG analysis showed no significant changes in the relative power [30].

In addition, increased absolute power on the gamma band [38] and decreased absolute power of delta and beta bands are differentiating factors between addicts and healthy subjects [39], while this is not observed in the assessment of relative power. Previous studies have clearly revealed the need for assessment in a relative or absolute power spectrum. Therefore, the question arises as to which technique is verified by MOI; this issue can be further evaluated as a future research topic.

A feature usually evaluated in the analysis of brain signals is asymmetry, a condition in which global neural activity is not the same in the two hemispheres. This feature is used mostly for people whose left hemisphere activity is dissimilar to that of the right hemisphere and may differ from that of healthy people [40]. The brain signals of the two hemispheres are said to be in a state of asymmetry [41]. In this regard, some researchers suggest that anterior asymmetry patterns may predict anxiety symptoms and even depression symptoms [5] due to the greater relative right frontal EEG activity [5].

Changing conditions sometimes lead to alterations in brain activity, with asymmetry regarded as a feature for the analysis of brain signals. Lopez-Duran et al. showed that the harmful effects of stress exposure in children may dampen the pattern of frontal EEG asymmetry [28]. Also, the findings reported by Shim et al. suggest that after manual lymphatic drainage, frontal EEG asymmetry significantly decreases [42]. Also, left frontal activity at rest can be a response to negative memories and experiences [43].

On the other hand, MOI is probably unsuitable for symptoms in which there is a palpable abnormality in the low frequency of standard EEG. For instance, cases with brief depression and other concurrent symptoms have a significantly higher temporal delta amplitude on QEEG and inter-hemispheric temporal delta asymmetry [3].

In healthy subjects, significant differences in asymmetry have been observed in the eyes-open state in comparison with the eyes-closed state in all bands (based on RPS) (Figure 6). The asymmetry feature should indicate dramatic differences and disorders in the left hemisphere function with respect to the right hemisphere, which should not be presumably observed for healthy people. An increase in alpha band is observed due to synchronization in neuronal networks when the eyes are closed. Also, enhancement of low-frequency waves is expected for the brain signals of all scalp areas (Figure 6). However, due to its unacceptable sensitivity, this feature may not be considered suitable in most symptoms.

Interestingly, in the current study, asymmetry based on MOI did not present any significant differences between the eyes-open and eyes-closed states in any band (P>0.05) (Figure 7). Therefore, observation of difference in asymmetry (based on MOI) of a special symptom in compared to normative database can be important and consider as a feature for diagnosis of the symptom [44].

Instead of calculating the asymmetry of MOI in different frequency bands, the asymmetry of total MOI can be used to compare right and left hemisphere activities. Paired t-test showed no significant difference in the asymmetry of MOI [(F4-F3)/(F4+F3)] between the eyes-open and eyes-closed states (P=0.227). This feature may be useful for people who have very different right and left hemispherical activities, e.g., children with emotional and behavioral problems [44].

5. Conclusion

Based on the findings, MOI can be used to boost HFWs in the power spectrum of brain signals. This study demonstrated that the MOI of different frequency bands might be used as a feature for patients who have differences in high-frequency bands or right and left hemispherical performance, compared to healthy people. Therefore, in order to confirm the obtained results and to evaluate the applicability of MOI in neurosciences, use of MOI for the assessment of HFWs of brain signals in conditions, including ADHD, alcoholism, and autism is necessary and suggested for future research.

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