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Investigation of electrical brain activity related to movement: a review

The work is devoted to consideration of different problems which arise in studying of the movement-related brain activity. Changes in the cortex activity during performing of the movement both real and imagery represent neural networks formed for planning and performing of the particular motion.

The review of possible preprocessing methods of the registered brain activity for increasing significance of extracted features are shown. Regularities and patterns which take place before and after movement onset are described. The methods that suitable for connectivity estimations in case of cortico-muscular relationships and in case of evaluations between brain regions are shown. In addition, possibility of movement classification and prediction together with reconstruction of kinematics features of the motion are considered.

References 27, figures 2.

Keywords: EEG; EMG; movement-related cortical potentials; MRCP; event-related desynchronization; ERD; corticomuscular coherence; CMC; movement prediction; brain-computer interface; BCI.

Introduction

In the study of real movements first of all the relationship between the cortex activity and the electrical activity of the muscles responsible for the execution of certain movements is under consideration. In addition, relationships arising in the brain during the planning and execution of a movement that reflects the functional connections in the brain is also important. Many studies are focused on developing brain-computer interface (BCI) related to the imaging or execution of movements.

Brain activity can be recorded by using of electroencephalography (EEG), magnetoencephalography (MEG) and electrocorticography (ECoG). EEG is the most common method due to it is non-invasive compared to ECoG and simpler compared to EMG.

Muscle activity is recorded by using of electromyography (EMG).

The same brain areas are activated during imagination and the real action. In particular these are the parts of the neural system which are associated with preparing and commanding of movements: the premotor cortex, the dorsolateral prefrontal cortex, the inferior frontal cortex, the posterior parietal cortex, the cerebellum and the basal ganglia. The activation of the motor cortex (M1) during imaginary movements is still unclear because some studies found neural activation and others not [20]. PET and fMRI indicate involvement of the sensorimotor cortices in addition to other cortical regions during tasks that trigger dystonia [9]. It is making important the investigation of movement-related brain activity for studying different movement disorders and dysfunctions.

In fact, motor activity, both actual and imagined as well as somatosensory stimulation, modulates the μ-rhythm (8 – 13 Hz) [23]. The M1 cannot initiate a movement alone, but needs to be stimulated by neurons from the premotor cortex and the supplementary motor area (SMA), which support and coordinate the M1. One task of the premotor cortex is to provide sensory guidance of movement while the SMA is, among others, responsible for planning and coordination of more complex movements [20]. The networks engaged in the early “volitional” part of the task are widespread in many structures of the brain [10].

The motor cortex displays synchronized rhythmic activity modulated by motor behavior [7]. The main phenomena observed on brain activity during movement execution is event-related desynchronization (ERD). ERD is caused also by imagined movements and by intended movements [23].

The aim of this work are review of different branches of the movement-related brain activity investigation and definition of further research directions.

Data pre-processing

Data pre-processing is important for the further analysis of the recorded signals. In all cases band-pass filtering is the main step of pre-processing.

If the research is aimed to investigate the relationship between brain and muscle activities, the question arises of the need for EMG processing. For this purpose rectification is commonly used.

Rectification of the EMG signal enhances firing rate information [19]. But at the same time EMG rectification had inconsistent effects on the power and coherence spectra and obscured the detection of cortico-muscular coherence (CMC) in some cases. That's why rectification is inappropriate [15].

One of the main challenges that is imminent in EEG processing is that the EEG signals are very noisy, having low signal to noise ratio and large trial to trial variability [24]. The other problem that complicates investigations is a volume conduction.

Described below the processing examples can be used not only for EEG but also for MEG and ECoG to improve extraction of brain activity features.

In [1, 22] smoothing with a Savitzky-Golay filter was used for the low-pass filtering of ECoG. In [2] auto-correlation of the EEG signals was performed to enhance the weak brain signals and reduce noise.

The purpose of the spatial filter is to reduce the effect of spatial blurring from the raw signal. The most common spatial filters are small and large Laplacian, bipolar, common average referenced (CAR) and current source density (CSD).

The large Laplacian and CAR references are most suited for a BCI instead of the small Laplacian and ear reference. CAR (the mean of all electrodes as reference) show the best performance in case of imagery classification [26].

CSD (Laplacian based) is a spatial filtering technique reducing the redundancy and ambiguity of volume conduction measures in EEG, which used to work on reference free data. The use of a CSD greatly improved CMC [17].

CSP (common spatial pattern) is more complex method for spatial filtering based on a decomposition of the raw EEG signals into spatial patterns, which are extracted from two populations of EEG [23, 26]. CSP filters maximize the variance of the signal under one condition and minimize it for the other condition. In [14] discriminative spatial pattern (DSP) filtering was proposed to extract the amplitude features of slow potentials of the ICs (0.1-4 Hz) instead CSP.

In [12] the use of optimal spatial filters (OSF) was evaluated in case of analysis of ERD and movement related cortical potentials (MRCP).

The other important group of pre-processing methods includes different decomposition techniques. For further analysis can be used the envelope of the signals calculated by Hilbert transform, the fitted curves calculated using the sigmoid fitting function [10] or the time–frequency (TF) representations of single-trial EEG signals calculated using the complex Morlet's wavelet [12, 27].

Independent component analysis (ICA) can decompose the overlapping source activities constituting the scalp EEG into functionally specific components. ICA can be performed to identify and remove artifacts associated with eye-blinks and muscle activation [9, 14].

For noise removing from the EEG empirical mode decomposition (EMD) can be used. It decomposes a signal into harmonics of various frequencies. EMD is a data dependent decomposition method without assumptions about the stationarity [24].

Principal Component Analysis (PCA) is used for dimensionality reduction of EEG signals or extracting features. In [26] the PCA is applied to the training set to find the transformation matrix for calculation of the final features.

Cortico-muscular connectivity

Coherence and phase synchronization are the most common methods for estimation interdependencies between two signals, which were used for investigation the coupling between both EEG/EMG and EEG/EEG during different tasks. In [21] partial coherence was used instead of ordinary coherence to solve reference problem, in [25] Regression-CMC method was used for study EEG and EMG relationship.

Long-range task-related coupling between primary motor cortex (PMC) and multiple brain regions was found in the same frequency band [7]. The contralateral motor cortex drives muscle discharge in the beta (15-30 Hz) and Piper (30-60 Hz) bands. Coherence between cortex and muscle in the beta band is found during weak or moderate isometric contractions. CMC in the Piper band is evident during strong isometric contractions or during movements [3].

Cortico-muscular coherence is diminished during a movement and appears predominantly during periods of isometric contraction following the movement. CMC was present in the beta band during sustained contractions but vanished before movement onset, being replaced by transient synchronization in the alpha and gamma bands during dynamic force output [16]. CMC features have task, attention and age related modulations. The coherence is smaller during a compliant condition.

In acute stroke CMC frequency decreases on the affected side and CMC amplitude increases on the unaffected side. In the chronic period there was no inter-hemispheric difference in CMC parameters. The changes in CMC parameters in acute stroke could result from a decrease in inhibition [25].

EEGs over the contralateral sensorimotor cortex is coherent with EMG (mean frequency: 19 Hz, mean value: 0.12). The time lag from cortex to muscle, computed by "constant phase shift plus constant time lag model", in 14-50 Hz was 14 ms [17].

In [4] the delay between MEG and EMG signals was estimated from mutual phase relationships by using of synchronization index approach. Sources were found in the primary motor cortex (M1) contralateral to the contracted muscle. Significant coherence between EMG and M1 activity was seen in the 20 Hz frequency range.

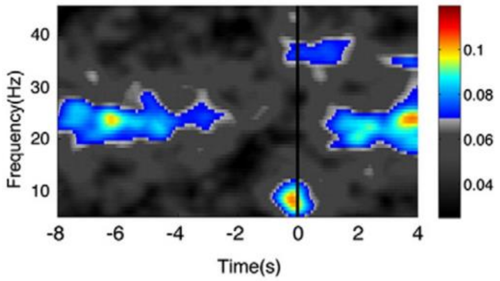

Figure 1. Time-frequency representation of CMC during exerting isometric force against the load cell [16]

Cortico-muscular synchronization from MEG and EMG in the beta band was found to be of particular importance in establishing bimanual movement patterns in the context of polyrhythmic isometric task [6].

In [18] the directed transfer function (DTF) was proposed for investigation of coupling between brain and muscles. DTF is useful in analyzing a reciprocally-connected system. Directional information flow from EEG to EMG reflects the motor control command. The finding of the directional information flow from EEG to EMG within the gamma band indicates that 40 Hz coherence is not specific to the muscle Piper rhythm which is seen only with strong contraction. Directional information flow computed from EEG to EMG was significant in the higher beta band (19-30 Hz).

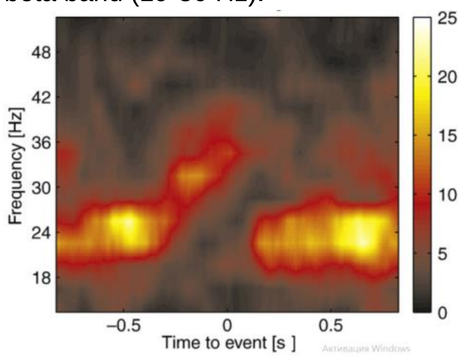

Figure 2. Rayleigh statistics of the phase-locking between M1 right and EMG left [6]

Movement-related brain activity

The largest, significant power decreases between pre and post unimanual conditions were found in the M1s opposite to the moving finger in all frequency bands. The largest, significant power increases were found in the cerebellar hemispheres [6]. The power spectrum of the activity in M1 during motor control shows a significant increase in the 3-5 Hz band compared with the rest condition [7]. A decrease in relative spectral power more prominent from 6 to 30 Hz, starting ~500 ms before movement onset, and an increase in spectral power in the range of 50-100 Hz, starting approximately 200 ms before movement onset [1].

In [7] using MEG and finger muscle recordings, the central origin of the peripheral ~8 Hz oscillations was revealed by showing that they were generated by an oscillatory network formed by the contralateral M1, the premotor cortex, the contralateral thalamus, and the ipsilateral cerebellum.

The planning and execution of movement leads to changes in the alpha and beta frequency bands, known as event-related desynchronization [27].

The main pattern, which occur in association with both real and imaginary voluntary movements is movement related cortical potential - MRCP. Its magnitude and latency are influenced by movement-related parameters [5].

MRCPs can be divided into 2 main components: a) the slow cortical potentials (SCPs) occurring during intention or anticipation of an upcoming movement and b) the motor potential (MP) occurring during the execution itself. The SCP is also known as the Bereitschaftspotential (BP) and has two phases: early - slow increase in negativity, and late - steeper slope [20]. The rebound after the peak of maximum negativity in MRCP has been associated with the precision of the movement [8].

Electro-cortical activity recorded during the preparation of the bimanually incompatible actions included a central positivity that began approximately 2.5 s before movement onset and was localized in medial frontal areas. Negative activity in the supplementary motor area takes place 700 ms before movement onset and a frontal lateral positivity emerged 1.8 s before the initiation of bimanual drawing task that was localized in the dorsolateral prefrontal cortex. All components are bilateral [13].

In [10] intracerebral electrodes during self-paced clenching movements of the hand were analyzed and two groups of signals were found: with EBS (Baseline shifts) and without. The onsets of EBSs were from 1.6 to 3.2 sec. 82 % of the EBSs started in various distant brain structures at the same time. The simultaneous EBS onsets suggest significantly higher functional coupling of some brain areas.

Connectivity between brain regions

Diverse neural networks with different resonance-like frequencies exist in the brain. In [21] premovement increase of coherence was shown between the SMA proper and S1-M1 at the frequency of 0–33 Hz and between the pre-SMA and S1-M1 at 0–18 Hz. Coherence between the SMA proper and M1 started to increase 0.9 sec before the movement onset and peaked 0.3 sec after the movement.

Coupling between the primary sensorimotor cortices in the beta frequency band was reduced with increasing movement speed. An increase of coherence was observed in the active as compared to the resting state.

In [11] directed coherence (from the dominant to the nondominant hemisphere) between C3 and C4 derivations was calculated. At rest, EEG-EEG directed coherence in the alpha frequency (0.05–0.23) was larger than in the beta frequency band (0.04–0.11). Coherence in the alpha frequency band decreased during bilateral compared with unilateral task. Statistical effects of force and condition (unilateral or bilateral) on normalized directed coherence from the dominant to the nondominant hemisphere were found in the alpha band. EEG-EEG coherence from the nondominant to the dominant hemisphere showed an effect of force but not condition.

In [9] coherence changes were investigated in individuals with arm dystonia. Ipsilesional sensorimotor cortical activation in the 8–12 Hz range is abnormally reduced in patients and correlates with weakness of the more affected wrist. Coherence at the rest was significantly lower in patients than controls.

Movement classification and prediction

Wavelet coefficients, power spectral density and average power, wavelet packet along with Fourier transform, wavelet packet entropy of EEG data can be used as features for classification [2]. In addition, statistical differences in ERD and MRCP correlates between different types of movements allow to use them for distinguishing between different motor tasks [12].

In [2] the EEG signals are decomposed into several bands of real and imaginary coefficients using dual-tree complex wavelet transform (DTCWT). The energy of the coefficients from relevant bands have been extracted as features.

In [8] a technique for discriminating between different levels of force and speed has been proposed by using the marginal distribution of optimized wavelets. Six temporal features were used from the initial negative phase of the MRCP until the point of detection to predict which of the four tasks the subjects intended to do.

In case of few electrodes are available, adaptive autoregressive filtering or finite impulse response multilayer perceptrons can be used as classifiers [23].

Among different types of classifiers developed K-nearest neighbor classifier has been shown to provide a good mean accuracy of ~91 % which is better than several existing techniques for imagery movements with using of energy of the DTCWT coefficients as features [2].

In [8] the temporal features, extracted from the movement intention, were classified with an optimized support vector machine. The system detected 81% of the movements and correctly classified 75±9% and 80±10% of these at the point of detection when varying the force and speed, respectively. The movements were detected 317 ±73 ms before the movement onset.

In [5] the single-trial EEG traces were classified with a pattern recognition approach based on wavelet coefficients as features and support vector machine as classifier. The movements of right foot with two different contraction torques and two rates of torque were classified with misclassification less than 30 %.

Movement kinematics from brain activity

Brain activity has been shown to correlate strongly with movement velocity independent of movement direction and coordination. Yet how neural oscillations might be related to limb speed control is still poorly understood [7].

Activity before movement onset from PMC recorded by ECoG from the region showing hand motor responses carries most directional information [1].

In [27] was demonstrated by using a single linear equation, that the parameters of the clenching speed as well as the hand are simultaneously embedded in the multi-channel EEG modulations associated with movement.

In [22] trajectories of 2D hand position was predicted from the ECoG data. The prediction performance for the random signals with the same auto-correlation as the ECoG signals is ~0, so correlations between real and predicted trajectories obtained from the ECoG really stem from informational content in the ECoG rather than from general signal properties. The ECoG signals are correlated to several movement parameters, including position, velocity and acceleration.

Most of the hand velocity energy during movements investigated in [7] was concentrated in the low-frequency range (<5 Hz). Hand speed is coherent with the activity of the contralateral primary motor and sensory areas in the 2-5 Hz range, with maximum coherence located on the precentral gyrus. In [14] was found that also 24-28 Hz band may carry the information of hand velocity.

In [1] the ECoG signals were decoded on a single-trial basis by regularized linear discriminant analysis. In [22] predictions were made using mutually exclusive test by using of the Kalman filter with average correlation coefficient ~0.4. In [14] hand movement velocity was reconstructed during a drawing task by Kalman filtering and a smoothing algorithm with average Pearson correlation coefficients ~0.37 for the h-dimension and ~0.24 for the v-dimension.

The extraction of kinetic information from the movement intentions in EEG signals can be done using the marginal distribution of the discrete wavelet transform (DWT) and the temporal features from EEG signals [24].

Conclusions

Investigations of movement-related electrical brain activity provide insight about mechanisms that take place in the cortex during preparation and execution of different movements. Functioning of neural networks formed due to movement condition can be studied in case of interdependencies estimations.

Various combinations of preprocessing methods can be used to increase the significant information from brain activity pertaining to movement features. The most complicated but promising methods are techniques of signal decomposition on different components such as ICA, ERD or wavelet decomposition, which allow to allocate particular components reflected just movement-related brain activity.

The most important researches are focused on classification of different movements and movement prediction which can be used for brain-computer interface and rehabilitation systems. Improvement of movement classification and prediction is possible by extracting the features of cortex activity that best describe the changes in the brain in case of movement. As such features CMC estimations obtained by using of EMG data can be used.

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Исследование электрической активности мозга, связанной с движениями: обзор

Работа посвящена рассмотрению проблем, возникающих при изучении деятельности мозга, связанной с движениями. Изменения в коре головного мозга во время выполнения движения, а также его представления, отображают нейронные сети, сформированные для планирования и реализации конкретного движения.

Приведен обзор методов первичной обработки зарегистрированной активности головного мозга, которые могут быть использованы для повышения значимости выделенных признаков. Описаны закономерности, которые имеют место до начала движения и после него. Представлены методы, подходящие для оценки связи как между активностью мозга и активностью мышц, так и между активностью областей головного мозга. Кроме того, рассмотрена возможность классификации и прогнозирования движений вместе с реконструкцией кинематических свойств. Библ. 27, рис. 2.

Ключевые слова: *ЭЭГ; ЭМГ; мозговые потенциалы связанные с движениями, МПСД; десинхронизация связанная с событием; ДСС; кортико-мышечная когерентность; КМК; прогнозирование движения; интерфейс мозг-компьютер; ИМК.*

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Дослідження електричної активності мозку, пов'язаної з рухами: огляд

Робота присвячена розгляду проблем, що виникають при дослідженні діяльності мозку, пов'язаної з рухами. Зміни в корі головного мозку під час виконання руху, а також його уявлення, відображають нейронні мережі, сформовані для планування і реалізації конкретного руху.

Наведено огляд методів первинної обробки зареєстрованої активності головного мозку, які можуть бути використані для підвищення значимості виділених ознак. Описано закономірності, які мають місце до початку руху і після нього. Представлені методи, які підходять для оцінки зв'язку як між активністю мозку і активністю м'язів, так і між активністю областей головного мозку. Крім того, розглянута можливість класифікації та прогнозування рухів разом з реконструкцією кінематичних властивостей. Бібл. 27, рис. 2.

Ключові слова: *ЕЕГ; ЕМГ; мозкові потенціали пов'язані з рухами; МППР; десинхронізація пов'язана з подією; ДПП; кортико-м'язева когерентність; КМК; прогнозування руху; інтерфейс мозок-комп'ютер; ІМК.*

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