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About the cortical origin of the low-delta and high-gamma rhythms observed in EEG signals during treadmill walking

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HIGHLIGHTS

- Spectral and time–frequency EEG analysis was performed in ambulatory context.
- Motion artifacts may affect EEG signal integrity up to 15 Hz.
- EEG and accelerometer signals exhibit similar time–frequency properties.
- Cortical origin of low-delta and high-gamma bands during locomotion is put in doubt.

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ABSTRACT

This paper presents a spectral and time–frequency analysis of EEG signals recorded on seven healthy subjects walking on a treadmill at three different speeds. An accelerometer was placed on the head of the subjects in order to record the shocks undergone by the EEG electrodes during walking. Our results indicate that up to 15 harmonics of the fundamental stepping frequency may pollute EEG signals, depending on the walking speed and also on the electrode location. This finding may call into question some conclusions drawn in previous EEG studies where low-delta band (especially around 1 Hz, the fundamental stepping frequency) had been announced as being the seat of angular and linear kinematics control of the lower limbs during walk. Additionally, our analysis reveals that EEG and accelerometer signals exhibit similar time–frequency properties, especially in frequency bands extending up to 150 Hz, suggesting that previous conclusions claiming the activation of high-gamma rhythms during walking may have been drawn on the basis of insufficiently cleaned EEG signals. Our results are put in perspective with recent EEG studies related to locomotion and extensively discussed in particular by focusing on the low-delta and high-gamma bands.

1. Introduction

Recently, numerous experimental results have indicated a strong involvement of the brain during locomotion. Significant changes in motor and cognitive demands (i.e. spatial attention) have been observed in the context of bipedal walking in unknown or cluttered dynamic environments [8,12,21,25]. Functional neuroimaging studies have shown that the primary motor cortex is recruited during rhythmic foot or leg movements [9,11,16,17,19,26]. Additionally, the technique of functional near-infrared spectroscopy (fNIRS) has allowed to detect involvement of frontal, premotor and supplementary motor areas during walking [15,28].

All those results were obtained using imagery techniques which are characterized by a good spatial but poor temporal resolution. In contrast, electroencephalography (EEG) is a measurement technique offering a sufficiently good temporal resolution to study the dynamics of brain. However, EEG study of cortical activity elicited during walk is highly challenging: EEG signals are by essence noisy and may be affected by different artifacts generated either by extracerebral physiological activity or by the gait itself [7].

Two strategies have thus been developed in the literature in order to overcome these experimental difficulties. The *static approach* consists in focusing on simplified foot or leg movements which imply common cerebral processes with gait. In these experimental protocols, subjects are mainly static and produce only limited lower limb movements. On the other hand, the *dynamic approach* consists in recording EEG signals from subjects walking on a treadmill. In this case, a powerful analysis technique to discriminate the different artifact contributions from the real cortical signals is of course required. Regrettably, the results of those different analyses are most of the time partially, if not totally,

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incompatible regarding both the location of the brain areas activated and the frequency bands of interest [5,6].

In this paper, the EEG signals recorded during treadmill walking are analyzed and compared with data acquired by an accelerometer placed on the head of each subject. Similarities between both types of signals are presented and extensively discussed in order to bring new clues in the general understanding of EEG signals recorded during human locomotion, in particular for the very low and very high frequency bands.

2. Materials and methods

2.1. Data collection

Seven healthy volunteers (5 males and 2 females) without any known physical or neurological disorders participated in this experiment (age-range: 25–33 years) whose protocol was extensively described elsewhere [7]. Basically, one of the objectives of this data collection was to assess the feasibility of developing a brain–computer interface under ambulatory conditions. Therefore, each subject walked bare feet on a treadmill at 1.5, 3 and 4.5 km/h wearing an EEG cap (32 passive electrodes) connected to the Advanced Neuro Technology amplifier (ANT, Enschede, The Netherlands) digitizing the signals at 512 Hz. Additionally, a piezoelectric accelerometer (Dytran 3100B) was fixed to a rigid plate mounted on a three-point linkage, firmly strapped on the head of the subject with an elastic band and plugged into the ANT system (see Fig. 3, supplementary material). This montage ensured the correct transmission of shocks to the accelerometer. Simultaneously, the kinematics of the lower limb movements was recorded using a system of six infrared cameras (Bonita, Vicon, Los Angeles, USA). Each EEG recording (i.e. 3 per subject) lasted about 12 min. All procedures were approved by the Université Libre de Bruxelles Internal Review Board and complied with the standards defined in the Declaration of Helsinki.

2.2. Pre-processing and spectral analysis

In a first step, the times of important gait events were determined with the kinematics data. Two principal events are defined in human locomotion: the *heel strike*, which is the time of the first contact of the foot with the ground, and the *toe off*, which is the last instant of contact of the foot with the ground. Consequently, 4 typical events follow one another during a gait cycle: the *right heel strike* (RHS), the *left toe off* (LTO), the *left heel strike* (LHS) and finally the *right toe off* (RTO) before the next RHS. During walking on the treadmill, the heel strike time is defined when the position of the malleolus marker is the most forward (in the treadmill axis direction), while the toe off time is defined when the fifth metatarsal marker is in the most backward position [33].

EEG signals were processed using the EEGLAB toolbox [10]. A standard spectral analysis (FFT) was made in order to compare the frequency contents of EEG electrodes and the accelerometer. The goal of such analysis was to check the possible presence of common harmonics associated to the stepping frequency of each subject. We focused on Cz, Oz and T8, for the diversity of their spatial localizations (top, back and left side of the head respectively) and thus for the diversity of the brain areas which are monitored.

2.3. Ensemble averaged time–frequency analysis

A time–frequency analysis was conducted in order to compare the signals coming from the EEG electrodes and the accelerometer, on a gait cycle basis. With this aim, EEG data were first detrended and then epoched by defining a time-window of 2 s around each left heel strike. Each epoch was visually inspected, rejected in case of obvious presence of eye or muscle artifacts.

As the lower limb movements during locomotion are only quasi-periodic, the stride length varies from one step to the other. The generation of precise ensemble averaged event-related spectral perturbation (ERSP) plots is thus not straightforward. We first computed spectrograms for each EEG channel during each epoch for each subject, as described in [14]. All the single-trial spectrograms were then linear time-warped so that the times of heel strikes and toe off events occurred at the same adjusted latencies. After this operation, spectrograms were ensemble averaged for all subjects. The average log spectrum for all movement cycles was subtracted from the log spectrogram for each movement cycle. The resulting changes from baseline are the ERSP plots presented in next section, as a function of the percentage of the normalized gait cycle. Significant ERSPs ($p < 0.05$) were computed using a bootstrapping method [10].

3. Results

Common harmonics were found in the spectra of EEG electrodes and the accelerometer. These harmonics correspond to the fundamental stepping frequency of the subjects, which ranges from about 0.6 Hz at 1.5 km/h to 1 Hz roughly at 4.5 km/h. Box-plots shown in Fig. 1 clearly indicate that the number of harmonics present in the spectra is monotonously increasing with the walking speed. Here, harmonics with Signal to Noise Ratio >2 are considered, the signal being the peak amplitude at frequency f (multiple of the fundamental) and the noise being the background amplitude evaluated in the $[f-0.5, f+0.5]$ Hz interval. At 4.5 km/h, up to 15 harmonics are observed in the EEG electrode spectra and almost twice as much in the accelerometer spectra. More precisely, harmonics are produced up to 15 Hz and 30 Hz in EEG and accelerometer signals respectively. In these conditions, delta, theta, alpha and low beta bands are impacted. Also, the distributions of harmonic numbers are obviously differing from one electrode to the other, meaning that the phenomenon giving rise to the harmonics most likely depends on the electrode spatial localization.

Regarding the time–frequency analysis, it appears that an event-related synchronization (ERS) is produced in the accelerometer signal at each heel strike, during the double support phase of gait, while an event-related desynchronization (ERD) appears during each swing phase (cf. Fig. 2), regardless of the walking speed (see additional material). Both ERD and ERS occur in a large frequency interval ranging from low-delta band up to high-gamma band (150 Hz) without any discontinuity (although inaccurate for an accelerometer, we use the terms ERS and ERD to describe more easily our observations). The same characteristic alternation (i.e. ERD–ERS) is visible in EEG electrodes Cz, Oz and T8 at 3 and 4.5 km/h, but with discontinuities along the frequency axis which vary both in number and localization according to the EEG electrode. Interestingly, the results obtained for the lowest walking speed (1.5 km/h) look different. Indeed, a specific succession of ERS–ERD–ERS occurs below 10 Hz, starting at each gait event (i.e. both heel strikes and toe offs) in all EEG electrodes, while the standard ERD–ERS alternation found at higher walking speeds is seen in the accelerometer channel.

4. Discussion

In addition to "traditional" EEG artifacts (ocular, muscular, power line, . . .), EEG recordings realized in ambulatory conditions are degraded by specific sources of noise [6,7]. *Triboelectric* noise is generated by movement, friction and flexion of the cable components, resulting in a static or piezoelectric movement transducer