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Selection of Task-Related Cortical EEG Sources for Brain-Computer Interface Applications

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Abstract. Electroencephalographic data (64 channels) collected from five normal healthy subjects during imagination of unilaterlal limb movements were used to compute scalp Event Related Potentials on electrodes over the sensorimotor areas and Cortical Current Density (CCD) waveforms on cortical Regions of Interest (RoIs) segmented on the motor, premotor and somatosensory areas. CCD was computed using (i) realistic three-shell Boundary Element Models for the head of each subject, (ii) distributed, surface constrained, normally-oriented cortical source model, (iii) regularized, minimum-norm weighted inverse problem solution. The working hypothesis was that task related features, such as lateralization of electrical activity which is expected to be contralateral to the movement that was imagined, would be more evident on the non-invasively estimated CCDs rather than in the scalp ERPs. Results show that the peak of activity is mainly located over the contralateral sensorimotor EEG channels and cortical RoIs. The lateralization of the activity is clearer on the CCD signals rather than on the ERP signals. These results suggest that the use of CCDs from task related cortical regions of interest as an input to Brain Computer Interface systems could be potentially superior with respect to the use of surface EEG potentials.

Keywords: Brain Computer Interface, high resolution EEG, Imagination of movements

1. Introduction

In these last years, it has been shown that the imagery of upper limb movements produced stable EEG patterns on the scalp surface, and that these patterns can be used in the build up of a Brain Computer Interface (BCI) system between a man and a computer [Birbaumer et al., 1999, Pfurtscheller G. and Neuper, 2001, Wolpaw et al., 2002]. The EEG patterns related to motor imagery are generally located in the centroparietal scalp areas, roughly overlying the primary sensory and motor cortical areas [Pfurtscheller and Neuper, 1997, Neuper et al., 1999, McFarland et al., 2000]. However, several published papers have also underlined the usefulness to collect brain information related to motor imagery by intracranial recordings in both humans [Kennedy and Bakay, 1998, Levine et al., 1999, Kennedy et al., 2000, Levine et al., 2000] and monkeys [Nicolelis et al., 1998, Chapin et al., 1999, Taylor et al., 2002, Donoghue, 2002]. These intracortical recordings, often performed on the primary motor cortical areas, provided signals which allow the user to control virtual or physical devices. Despite of these successes, the use of intracranial recordings in humans is obviously limited for ethical reasons to those patients who undergo brain surgery or are severely disabled [Kennedy and Bakay, 1998, Levine et al., 1999]. However, a question arises about the possibility to avoid invasive recording procedures without to renounce to high quality of signals recorded at the cortical level.

Recently, it has been suggested that with the use of the modern high resolution EEG technologies [Gevins et al., 1990, Nunez, 1995, Babiloni et al., 2001] it could be possible to estimate the cortical activity associated to mental imagery of the upper limb movements in humans [Grave de Peralta Menendez et al., 2003, van Burik et al., 1999, Cincotti et al., 2002]. However, a verification of this statement on a group of normal subjects has not been performed yet.

The working hypothesis at the base of the present work was that task related features, such as the hemispheric lateralization of electrical activity, which is expected to be contralateral to the movement that was imagined, would be more evident on the non-invasively estimated Cortical Current Density distributions (CCDs) rather than in the scalp ERP maps and waveforms. This is expected since cortical primary areas involved in the imagination of hand movement have a limited extension, while, on the other hand, the smearing due to volume conduction does not allow such a detailed pattern to be represented in the scalp recorded potential distribution. In other words, the potential measured from an electrode overlaying the motor area does not only receive contribution from the signal of interest, but also from signals generated from the surrounding cortical areas, yielding a lower SNR with respect to an hypothetical electrocorticographic recording.

Estimating the cortical distribution of the sources should grossly restore the original spatial distribution, allowing a more effective recognition of relevant EEG features, unless the estimation error overcomes the expected advantage.

To address this issue, high resolution EEG recordings were obtained in a group of five healthy subjects during the imagination of upper limb movements. Comparisons between the waveforms from scalp electrodes and those from the estimated cortical activity in specific Region of Interest (ROIs) were then performed. By doing so, information about the advantages in using cortical activity to recognize mental states with respect to the use of the scalp recorded data are achieved.

2.Methodology

Data Collection.

Five right handed healthy volunteers participated to the experiments. Subjects were asked to perform the imagination of extension of all the fingers of the right hand; motor imagery task was self-paced with an interval of 6-7s. EEG was recorded by using a high resolution EEG cap with 58 electrodes disposed on the scalp accordingly to an extension of the 10-20 international system. EEG data sampling frequency was 200 Hz, and signal was bandpass filtered between 0.1 and 70 Hz before digitization. Electromyographic (EMG) signals were also recorded bilaterally from the Extensor Digitorum Comunis muscle, to check for any tiny muscle contractions of the fingers during performance of motor imagery. EMG signals were also recorded from lip muscle (Orbicularis Ori) by two additional electrodes placed symmetrically beside the mouth corner. Subjects were asked to imagine brisk movement of their right fingers and to signal the performance of motor imagery task by simultaneous brisk lip pursing. This was to provide the necessary EMG trigger to synchronize the average of recorded potentials. The performance of the task was stabilized before starting the recording. Subjects were trained to perform the lips pursing with a regular intensity and interval; then they were also asked to execute the actual extension of the fingers, to check that the instruction had been understood. Some trials of simultaneous finger extension and lips pursing were executed to check for synchronicity. Finally the "lips movement - hand imagination" task was repeated until the subject said he/she was comfortable with the task. This procedure was usually performed during the impedance lowering of scalp electrodes and lasted from 15 to 20 minutes. One hundred single EEG trials were recorded for each subject. Each single EEG trial was acquired from 2.5 second before task to 0.5 s after.

Head model.

For all subjects analyzed in this study, sequential MR images were acquired and realistic head models were generated. Scalp, skull, dura mater and cortical surfaces of the realistic and averaged head models were obtained with segmentation and contouring algorithms. The surfaces of the realistic head models were then used to build the Boundary Element Model of the head as volume conductor employed in the present study. Conductivities values for scalp, skull and dura mater were those reported in Oostendorp et al. [Oostendorp et al., 2000]. A cortical surface reconstruction was accomplished for each subject's head with a tessellation of about 10,000 triangles on average.

Figure 1. *The sensor configuration is derived with the help of a photogrammetric procedure, which consists in marking all the electrodes visible in a set of pictures taken immediately after the EEG acquisition is finished (one picture is shown in the left panel). Triangulation between the two-dimensional projections of each electrode onto the plane of the pictures provide their three-dimensional position. Matching the craniometric repere points, allows to express these positions in the same coordinate system as the head model derived from MRIs. Superimposition of the head model as seen from the camera position with the picture (right panel) offers the oportunity to visually check the accuracy of the alignment between sensor positions and BEM.*

Estimation of cortical source activity.

The estimation of cortical activity during the motor imagery task was performed in each subject by using the depth-weighted minimum norm algorithm [Babiloni et al., 2000, Babiloni et al., 2003]. This estimation returns a current density estimate for each one of the about five thousand dipoles constituting the modeled cortical source space. Each dipole returns a time-varying amplitude representing the brain activity of a restricted patch of cerebral cortex during the entire task time-course. This rather large amount of data can be synthesized by computing the ensemble average of all the dipoles magnitudes belonging to the same cortical region of interest (ROI). Each ROI was defined on each subject's cortical model adopted in accordance with its Brodmann's Areas (BAs). In the present study, the definition of the ROI of the left and right primary motor areas (MI) took into account those regions of the BA 4 relative to lips (MI-lips) and hand (MI-hand) somatotopic representation. This is shown in Figure 2 where the ROIs employed for each single subject over the realistic cortical and head model reconstructions are coded with different color: red for MI-hand, and blue for MI-lips. Primary motor areas have been segmented according to the

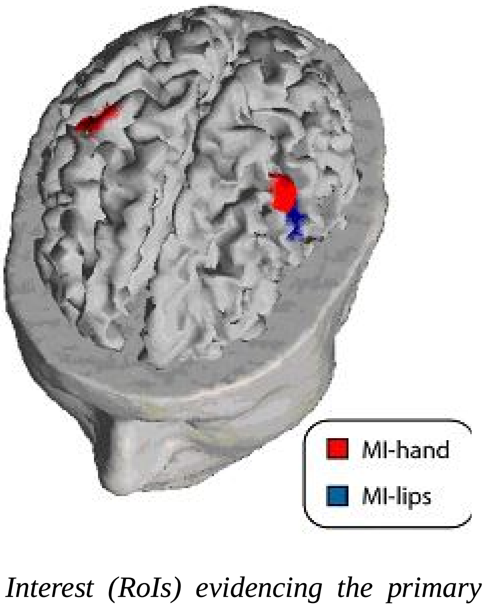

Figure 2. *Cortical Regions of Interest (RoIs) evidencing the primary motor cortices involved in movement of fingers (MI-hand) and lips (MI-lips) movement, in red and blue respectively, for a representative subjecs included in this study*

somatotopic organization of the motor cortex (motor "homunculus"), on the basis of the anatomical landmarks present in the precentral gyrus [Yousry et al., 1997]. Other parts of the cortical surface that were used for the estimation of the current density distribution, but not comprised in the statistical analysis of results, are visible in the figure colored in grey.

Data Analysis.

Single trials were inspected for artifact presence by an expert electroencephalographer. Causes of rejection were: EOG contamination (most frequently) higher than 50 µV on frontopolar derivations; EMG contamination, defined as high frequency activity over frontal and/or temporal and/or occipital derivations; Presence of actual muscle contraction during the imagination of movement; baseline wandering, due to movement artifacts or sweating; instrumental artifacts. This procedure returned about seventy five artifact free trials that were averaged. Potential waveforms from electrodes overlying MI-hand cortical areas (i.e. C3 and C4 positions of the 10-20 International System) were selected for later comparison with estimated cortical activations. The scalp potential distribution was then subjected to the linear inverse procedure, and the resulting time varying cortical current density distributions were estimated. The average of current density estimated on all sources belonging to each ROI provided the cortical waveform related to each particular ROI analyzed.

Results

The average activity observed at scalp electrodes and that estimated over the cortical ROIs showed consistent spatiotemporal patterns across all the experimental subjects performing motor imagery (Figure 3). These patterns were composed of a consistent negative activity distributed over the centro-parietal scalp regions. As expected, a clear negative potential distribution was observed over the centro parietal scalp areas with a time course starting about 1000 ms before the EMG trigger. This potential distribution resembles the motor potential observed over the centrolateral and mesial scalp areas during overt limb movements [Neuper et al., 1999, Babiloni et al., 1999]. A peak of negative activity was generated over both the vertex and the left lateral scalp areas and occurred within 100 ms following the EMG onset of lip movement. The time course of averaged potentials on the scalp areas ipsilateral to the imagined finger movements were of similar shape but of lower amplitude compared to contralateral ones.

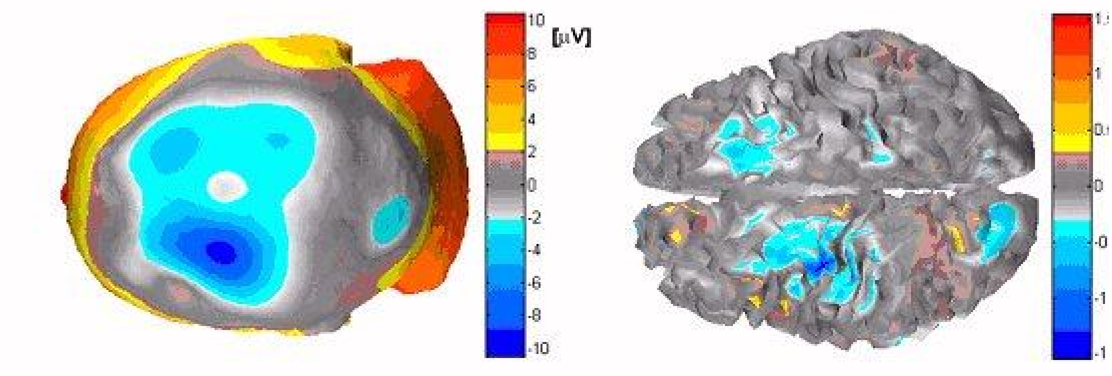

Figure 3. Scalp distribution of potential (left panel) and cortical distribution of current density (right panel). The pictures are relative to the averaged distribution at the time of the electromyographic onset during extension of the fingers of the right hand.

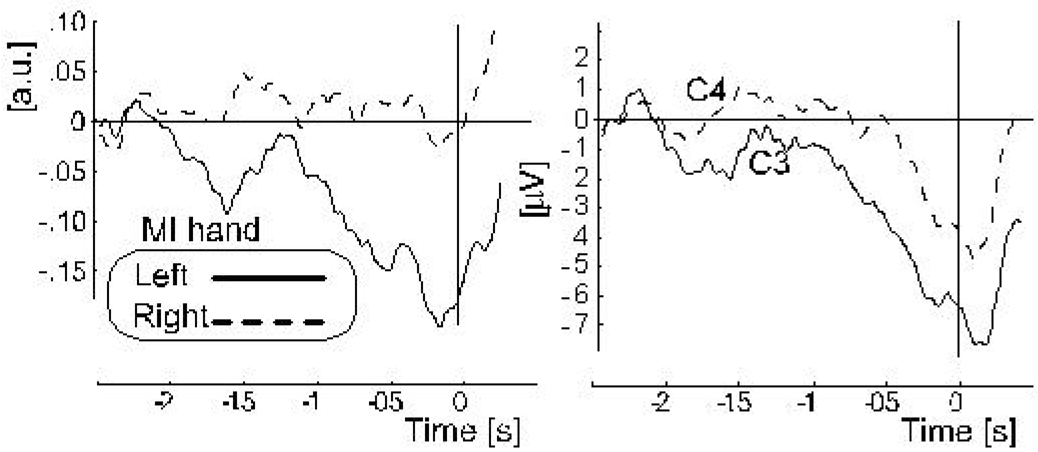

__Figure 4.__ Scalp Event Related Potentials on central electrodes (right panel) and Cortical Current Density estimates on primary motor areas (left panel) related to the imagination of movement of the right hand. CCD estimates show a more evident lateralization.

Table 1 reports the peak values [Barrett et al., 1986] of (i) potentials at C3 and C4 and of the bilateral (ii) MI-hand and (iii) MI-lips current densities for all subjects included in the study. Scalp potential amplitudes at peak are less unbalanced between left and right scalp areas when compared to the estimated current density in left and right MI-hand areas. The estimated cortical current density values for the MI-lips are rather symmetrical, i.e. the values are similar for the left and right ROIs.

__Table 1.__ Peak values of (i) potentials at C3 and C4 leads and of the bilateral (ii) MI-hand and (iii) MI-lips current densities for all subjects included in the study. C3 and C4 are the electrode position of the 10-20 international system that overly the sensorymotor hand area; MI-hand is the region of the pre-central gyrus involved in motor control of the hand muscles; MI-lips is the region of the pre-central gyrus involved in motor control of the lips muscles. Values for the C3 and C4 measurements are in uV, values for the current density measurements are in arbitrary units.

	C3	C4	Left MI-hand	Right MI-hand	Left MI-lips	Right MI-lips
Subject 1	-8.2	-5.4	-0.88	0.01	0.34	0.06
Subject 2	-8.6	-7.2	-0.57	-0.35	-0.48	-0.04
Subject 3	-12.5	-10.2	-1.42	-0.96	-0.81	-0.51
Subject 4	-5.8	-6.9	-0.68	-0.34	-0.37	0.38
Subject 5	-8.3	-5.4	-0.23	-0.02	-0.19	-0.13
p	0.04		0.01		0.11	

Statistical analysis of the interhemispheric unbalance in the gathered scalp potentials as well as in the estimated cortical activity was then performed by using the paired Student's t-test. The results obtained indicated; (a) a highly significant prevalence of cortical activity estimated over the primary motor cortical areas contralateral to the movement imagined (left MI-hand) with respect to the ipsilateral one (left MI-hand), with a significance p= 0.01; (b) a not significant difference between cortical activity estimated for the left and right MI-lips ROIs (p = 0.11); and (c) a statistically significant differences between the MP peak for the scalp potentials gathered from the left scalp areas (C3) with respect to the right (C4) one (p = 0.04).

4. Discussion

The data reported here suggest that it is possible to retrieve the cortical activity related to motor imagery by using sophisticated high resolution EEG techniques, obtained by solving the linear inverse problem with the use of realistic head models. Analysis of the distribution of the potential fields underlying motor imagery in humans have been already described [Pfurtscheller and Neuper, 1997, Neuper et al., 1999]. However, in the context of the Brain Computer Interface, it assumes importance whether the activity related to the imagination of arm movement could be unbalanced between the two hemispheres. Indeed, the greater this unbalance between the scalp activity gathered by scalp electrodes C3 and C4, the easier is the recognition task operated by a classifier [Neuper et al., 1999]. The relevant finding here is that the group analysis of the cortical waveforms associated to motor imagery reveals a more pronounced interhemispheric unbalance of the cortical activity estimated in the primary motor areas with respect to what observed for the scalp activity. Moreover, the interemispheric asymmetry detected in the estimated cortical activity of the primary motor areas during finger movement imagination, was not found for the primary motor area estimated activity related to lip pursing. The rather bilateral cortical activity for the lip cortices is consistent with the bilateral activations of primary motor regions corresponding to lip somatotopic rappresentation reported in a previous functional MRI (fMRI) study during lip overt movements [Lotze et al., 2001].

Several EEG or magnetoencephalographic studies have shown as the cortical activity related to motor imagery could be retrieved by using the single equivalent dipole approximation [Schnitzler et al., 1997, Hari et al., 1998, Green et al., 1999]. However, it must be noted that the use of single dipole is a rather crude approximation of the distributed cortical activation underlying mental imagery. Furthermore, the dipole localization technique is a non linear methodology, which involves the use of iterative algorithms for the search of the minimum of the cost functional associated with the optimal dipole position in the head model. This last aspect makes the dipole approximation an unsuitable tool for the on-line processing of the EEG data needed in a BCI device in order to return a useful feedback to the user [Gevins et al., 1990]. On the other hand, it is worth of note that the cortical estimation methodology illustrated above is suitable for the on-line applications needed for the BCI device. In fact, despite of the use of sophisticated realistic head models for scalp, skull, dura mater and cortical surface, the estimation of the instantaneous cortical distribution from the acquired potential measures required a limited amount of time necessary for a matrix multiplication. This multiplication occurs between the data vector gathered and the pseudoinverse matrix, that is stored off-line before the start of the EEG acquisition process. In the pseudoinverse matrix is enclosed the complexity of the geometrical head modeling with the Boundary Element or with the Finite Element Modeling techniques, as well as the a priori constraints used for the minimum norm solutions.

It may be argued if the weighted minimum norm approach to the estimation of current densities with the realistic head models has the spatial resolution needed to resolve the cortical processes generated on the brain surface. However, it should be noted that a simulation study suggested that the errors in localization o the cortical sources depends on the number of evenly spaced sources used to model the cortical surface [Babiloni et al., 2000]. The higher the number of such sources in the cortical structure adopted, the higher the accuracy of the current estimation. According to the results of simulations, the number of sources employed in the present study (about 5000) would yield an error below 4 mm in the primary motor areas. Such values are largely sufficient to estimate accurate cortical waveforms from the region of interests depicted around the primary motor areas considered in this study.

There is a wide trend in the modern neuroscience field to move toward invasive electrode implants for recording cortical activity in both animals and humans to implement an efficient BCI device [Chapin et al., 1999, Kennedy et al., 2000, Donoghue, 2002]. In this study, we present evidence in favour of an alternative methodology for the estimation of cortical activity non invasively, based on the possibilities offered by an accurate modeling of the principal head structures involved in the transmission of the cortical potential from the brain surface to the scalp electrodes.

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