CLUSTER STRUCTURE OF FUNCTIONAL NETWORKS ESTIMATED FROM HIGH-RESOLUTION EEG DATA

ROBERTA SINATRA
Complex Systems Laboratory,
Scuola Superiore di Catania, Catania, Italy
robertasinatra@gmail.com
rsinatra@ssc.unict.it

FABRIZIO DE VICO FALLANI
Interdepartmental Research Centre for Models and Information Analysis in Biomedical Systems,
University “La Sapienza”, Rome, Italy

LAURA ASTOLFI, FABIO BABILONI, FEBO CINCOTTI and DONATELLA MATTIA
IRCCS “Fondazione Santa Lucia”, Rome, Italy
Department of Human Physiology and Pharmacology,
University “La Sapienza”, Rome, Italy

VITO LATORA
Department of Physics and Astronomy,
University of Catania,
and INFN Sezione Catania, Italy

Received March 14, 2008; Revised April 9, 2008

We study the topological properties of functional connectivity patterns among cortical areas in the frequency domain. The cortical networks were estimated from high-resolution EEG recordings in a group of spinal cord injured patients and in a group of healthy subjects, during the preparation of a limb movement. We first evaluate global and local efficiency, as indicators of the structural connectivity respectively at a global and local scale. Then, we use the Markov Clustering method to analyze the division of the network into community structures. The results indicate large differences between the injured patients and the healthy subjects. In particular, the networks of spinal cord injured patient exhibited a higher density of efficient clusters. In the Alpha (7–12Hz) frequency band, the two observed largest communities were mainly composed of the cingulate motor areas with the supplementary motor areas, and of the premotor areas with the right primary motor area of the foot. This functional separation strengthens the hypothesis of a compensative mechanism due to the partial alteration in the primary motor areas because of the effects of the spinal cord injury.

Keywords: Community structure; network efficiency; cortical activity.

*Author for correspondence
The first two authors have contributed equally to the present paper.
1. Introduction
Over the last years, there has been an increasingly large interest in finding significant features from human brain networks. In particular, the concept of functional connectivity plays a central role to understand the organized behavior of anatomical regions in the brain during activity. This organization is thought to be based on the interaction between different specialized areas of cortical sites. Indeed, several methods have been proposed and discussed in the literature, with the aim of estimating the functional relationships among the physiological signals [David et al., 2004; Lee et al., 2003] obtained from different neuro-imaging devices such as the functional Magnetic Resonance Imaging (fMRI) scanner, electroencephalography (EEG) and magnetoencephalography (MEG) apparatus [Horwitz, 2003]. Recently, a multivariate spectral technique called Directed Transfer Function (DTF) has been proposed [Kaminski et al., 2001] to determine directional influences between any given pair of channels in a multivariate data set. This estimator is able to characterize at the same time direction and spectral properties of the brain signals, requiring only one multivariate autoregressive (MVAR) model to be estimated from all the EEG channel recordings. The DTF index has been demonstrated [Kaminski et al., 2001] to rely on the key concept of Granger causality between time series — an observed time series \( x(n) \) leads to another series \( y(n) \) if the knowledge of past \( x(n) \)s significantly improves the prediction of \( y(n) \) — [Granger, 1969]. However, the extraction of salient characteristics from brain connectivity patterns is an openly challenging topic, since often the estimated cerebral networks have a relative large size and complex structure. Consequently, there is a wide interest in the development of mathematical tools that could describe in a concise way the structure of the estimated cerebral networks [Tomoni et al., 1994; Stam, 2004; Salvador, 2005; Sporns, 2002].

Functional connectivity networks estimated from EEG or magnetoencephalographic (MEG) recordings can be analyzed with tools that have been already proposed for the treatments of complex networks as graphs [Strogatz, 2001; Wang & Chen, 2003; Sporns et al., 2004; Stam et al., 2006a]. Such an approach can be useful, since the use of mathematical measures summarizing graph properties allows for the generation and the testing of particular hypothesis on the physiologic nature of the functional networks estimated from high-resolution EEG recordings. However, first results have been obtained for a set of anatomical brain networks [Sporns, 2005; Sporns et al., 2007]. In these studies, the authors have employed two characteristic measures, the average shortest path \( L \) and the clustering index \( C \), to extract respectively the global and local properties of the network structure [Watts & Strogatz, 1998]. They have found that anatomical brain networks exhibit many local connections (i.e. a low \( L \)). Hence, anatomical brain networks have been designated as small-world in analogy with the concept of the small-world phenomenon observed more than 30 years ago in social systems [Milgram, 1967].

Many types of functional brain networks have been analyzed in a similar way. Several studies based on different imaging techniques like fMRI [Salvador et al., 2005; Eguiluz et al., 2005; Achard & Bullmore, 2007], MEG [Stam et al., 2006a, 2006b; Bassett et al., 2006; Bartolomei et al., 2006] and EEG [Micheloyannis et al., 2006; Stam et al., 2007] have shown that the estimated functional networks can indeed exhibit the small-world property. In the functional brain connectivity context, these properties have been demonstrated to reflect an optimal architecture for the information processing and propagation among the involved cerebral structures [Lago-Fernandez et al., 2000; Sporns et al., 2000]. In particular, a high clustering index \( C \) is an indication of the presence in the network of a large number of triangles. However, this index alone does not return detailed information on the presence of larger connected clusters of nodes. This fact makes up a real obstacle in the analysis of the network properties, especially in the field of the Neuroscience where the correlated behavior of different cortical regions plays a fundamental role in the correct understanding of cerebral systems. Methods to detect the community structures in a graph, i.e. tightly connected group of nodes, are now available in the market [Harary & Palmer, 1972]. Communities (or clusters or modules) are groups of vertices that probably share common properties and/or play similar roles within the graph [Boccaletti et al., 2006]. Hence, communities may correspond to groups of pages of the World Wide Web dealing with related topics [Flake et al., 2002], to functional modules such as cycles and pathways in metabolic networks [Guimerà & Amaral, 2005; Palla et al., 2005], to groups of
Cluster Structure of Functional Networks Estimated from High-Resolution EEG Data

2. Methods

2.1. High-resolution EEG recordings in SCI patients and healthy subjects

All the experimental subjects participating in the study were recruited by advertisement. Informed consent was obtained for each subject after the explanation of the study, which was approved by the local institutional ethics committee. The spinal cord injured (SCI) group consisted of five patients (age 22–25 years; two females and three males). Spinal cord injuries were of traumatic aetiology and not suffered from a head or brain lesion associated with the trauma leading to the injury. The control (CTRL) group consisted of five healthy volunteers (age 26–32 years; five males). They had no personal history of neurological or psychiatric disorder; they were not taking medication, and were not abusing alcohol or illicit drugs. For EEG data acquisition, subjects were comfortably seated on a reclining chair, in an electrically shielded, dimly lit room. They were asked to perform a brisk protrusion of their lips (lip pursing) while they were performing (healthy subjects) or attempting (SCI patients) a right foot movement. The choice of this joint movement was suggested by the possibility to trigger the SCIs attempt of foot movement. In fact, patients were not able to move their limbs; however they could move their lips. By attempting a foot movement associated with a lips protrusion, they provided an evident trigger after the voluntary movement activity. This trigger was recorded to synchronize the period of analysis for both the considered populations. The task was repeated every 6–7 seconds, in a self-paced manner, and the 100 single trials recorded will be used for the estimate of functional connectivity by means of the Directed Transfer Function (DTF; see following paragraph). A 96-channel system (BrainAmp, Brainproducts GmbH, Germany) was used to record EEG and EMG electrical potentials by means of an electrode cap and surface electrodes, respectively. The electrode cap was built accordingly to an extension of the 10–20 international system to 64 channels. Structural MRIs of the subjects head were taken with a Siemens 1.5T Vision Magnetom MR system (Germany).

2.2. Cortical activity and functional connectivity estimation

Cortical activity from high-resolution EEG recordings was estimated by using realistic head models and cortical surface models with an average of 5,000 dipoles, uniformly disposed. Estimation of the current density strength, for each one of the 5,000 dipoles, was obtained by solving the Linear Inverse problem, according to techniques described in previous papers [Babiloni et al., 2005; Astolfi et al., 2006]. By using the passage through the Talairach coordinates system, twelve Regions Of Interest (ROIs) were then obtained by segmentation of the Brodmann areas on the accurate cortical model utilized for each subject. The ROIs considered for the left (\(\mathcal{L}\)) and right (\(\mathcal{R}\)) hemispheres are: the primary motor areas for foot (MF\(_\mathcal{L}\) and MF\(_\mathcal{R}\)) and lip movement (ML\(_\mathcal{L}\) and ML\(_\mathcal{R}\)); the proper supplementary motor area (SM\(_\mathcal{L}\) and SM\(_\mathcal{R}\)); the standard premotor area (6\(_\mathcal{L}\) and 6\(_\mathcal{R}\)); the cingulated motor area (CM\(_\mathcal{L}\) and CM\(_\mathcal{R}\)) and the associative Brodmann area 7 (7\(_\mathcal{L}\) and 7\(_\mathcal{R}\)). For each EEG time point, the magnitude of the five thousand dipoles composing the cortical model was estimated...
by solving the associated Linear Inverse problem [Grave de Peralta & Gonzalez Andino, 1999]. Then, the average activity of dipoles within each ROI was computed. In order to study the preparation to an intended foot movement, a time segment of 1.5 seconds before the lips pursing was analyzed; lips movement was detected by means of an EMG. The resulting cortical waveforms, one for each predefined ROI, were then simultaneously processed for the estimation of functional connectivity by using the Directed Transfer Function. The DTF is a full multivariate spectral measure used to determine the directed influences between any given pair of signals in a multivariate data set [Kaminski et al., 2001]. In order to be able to compare the results obtained for data entries with different power spectra, the normalized DTF was adopted. It expresses the ratio of influence of element $j$ to element $i$ with respect to the influence of all the other elements on $i$. Details on the DTF equations in the treatment of EEG signals have been largely described in previous papers [Astolfi et al., 2005; Babikien et al., 2005]. In the present study, we selected four frequency bands of interest (Theta 4–7 Hz, Alpha 8–12 Hz, Beta 13–29 Hz and Gamma 30–40 Hz) and we gathered the respective cortical networks by averaging the values within the respective range. In order to consider only the functional links that are not due to chance, we adopted a Monte Carlo procedure. In particular, we contrasted each DTF value with a surrogate distribution of one thousand DTF values obtained by shuffling the signal samples in the original EEG data set. Then, we considered a threshold value by computing the 99th percentile of the distribution of one thousand DTF values obtained for data entries with different power spectra. Separate ANOVAs were conducted for each of the two variables (also unconnected) networks related to efficiency [Latora & Marchiori, 2001, 2003]. The efficiency $e_{ij}$ in the communication between two nodes $i$ and $j$ is defined as the inverse of the shortest distance between the vertices. Note that in weighted graphs the shortest path is not necessarily the path with the smallest number of edges. In the case when the two nodes are not connected, the distance is infinite and $e_{ij} = 0$. The average of all the pair-wise efficiencies $e_{ij}$ is the global-efficiency $E_g$ of the graph $G$:

$$E_g(G) = \frac{1}{N(N-1)} \sum_{i \neq j \in G} \frac{1}{d_{ij}}$$

where $N$ is the number of vertices composing the graph. The local properties of the graph can be characterized by evaluating for every vertex $i$ the efficiency of $G_i$, which is the subgraph induced by the neighbors of the node $i$ [Latora & Marchiori, 2001]. Thus, we defined the local-efficiency $E_l$ of graph $G$ as the average:

$$E_l(G) = \frac{1}{N} \sum_i E_g(G_i).$$

Since node $i$ does not belong to subgraph $G_i$, the local efficiency measures how the communication among the first neighbors of $i$ is affected by the removal of $i$ [Latora & Marchiori, 2005, 2007]. Hence, the local efficiency is an indicator of the level of fault-tolerance of the system. Separate ANOVAs were conducted for each of the two variables $E_g$ and $E_l$. Statistical significance was fixed at 0.05, and main factors of the ANOVAs were the “between” factor GROUP (with two levels: SCI and CTRL) and the “within” factor BAND (with four levels: Theta, Alpha, Beta and Gamma). Greenhouse & Geisser correction has been used for the protection against the violation of the sphericity assumption in the repeated measure ANOVA. Besides post-hoc analysis with the Duncan’s test and significance level at 0.05 has been performed.

### 2.4. Detection of community structures

In order to detect the community structures, we have implemented the Markov Clustering (MCl)
3. Results

Figure 1 shows the realistic head model obtained for a representative subject. The twelve ROIs used in the present study are illustrated in color on the cortex model that is gray colored. At the bottom of Fig. 1, we report the adjacency matrices representing the cortical networks estimated in the Alpha frequency band, from the two analyzed populations during the movement preparation. Note that such networks are directed. Consequently, the obtained adjacency matrix is not symmetric. The level of gray within each matrix in figure encodes the number of subjects that hold the functional connection identified by row i and column j.

As a measure of global and local performances of the network structure we have evaluated the global-efficiency $E_g$ and the local-efficiency $E_l$ indices obtained for each frequency band and for each subject. The average values of $E_g$ and $E_l$ derived from the healthy group (CTRL) and from the group of patients (SCI) are illustrated for each band in the scatter plot in Fig. 2. We have performed an Analysis of Variance (ANOVA) of the obtained results. The $E_g$ variable showed no significant differences for the main factors GROUP and BAND. In particular, the “between” factor GROUP was found having an F value of 0.83, p = 0.392 while the “within” factor BAND showed an F value of 0.002 and p = 0.99. The ANOVA performed on the $E_l$ variable revealed a strong influence of the between factor GROUP ($F = 32.67$, p = 0.00045); while the BAND factor and the interaction between GROUP X BAND was found not significant ($F = 0.21$ and $F = 0.91$, respectively, p values equal to 0.891 and 0.457). Post-hoc tests revealed a significant difference between the two
examined experimental groups (SCI, CTRL) in the Alpha and Beta band ($p = 0.01, 0.03$, respectively). In particular, the average local-efficiency of the SCI networks was significantly higher than the CTRL networks for all these bands.

The identification of functional clusters within the cortical networks estimated in the control subjects and in the spinal cord injured patients during the movement preparation was addressed through the MCl algorithm (see Methods — Detection of Community Structures (2.4)). In Fig. 3 the average number of clusters detected in the CTRL and SCI networks is reported as a function of the granularity parameter $r$. As it can be observed, for every value of $r$, and for both the Alpha and Beta bands, the average number of clusters is greater for the SCI group than for the CTRL one. One of the main problems with the MCI algorithm is the choice of the value of the granularity parameter to be used. Usually, good values of $r$ are in the range $[1, 3]$ [Van Dongen, 2000; Enright et al., 2002]. For the case under study here, the presence of a plateau in Fig. 3 indicates that there is a region of values such that the number of clusters does not strongly depend on $r$. We have decided to adopt the granularity $r = 1.5$ that is a value in the plateau. For this value of $r$, the average number of clusters in the Alpha band is equal to 3.2 for the cortical networks of the control subjects, while it is equal to 5 for the spinal cord injured patients. In the Beta band, the average
number of cluster is 3.4 for the CTRL networks and 4.6 for the SCI networks, as can be observed at the bottom in Fig. 3.

Figure 4 illustrates the partitioning of the cortical networks estimated in the Alpha band for a representative subject of the control (CTRL) group and for a representative patient of the spinal cord injured (SCI) group.

Functional networks are represented as three-dimensional graphs on the realistic head model of the experimental subjects. The color of each node, located in correspondence to each cortical area (ROI), encodes the cluster to which the node belongs. The functional clusters detected within the cortical networks in all the subjects and patients participating in the present study are listed in the following tables. Table 1 presents the results obtained in the Alpha band while Table 2 presents the results obtained in the Beta band.

In the Alpha band, the CTRL networks do not present a particularly complicated division into clusters, since for each subject the large part of the cortical areas belong to a unique large community (Cluster 1). In general, the SCI networks organized in a larger number of clusters are more clustered, and two main communities can be observed (Clusters 1 and 2). The first community is mostly composed of the cingulate motor areas (CM_L and CM_R), the supplementary motor areas (SM_L and SM_R) and the left primary motor area (MF_L). The second community is predominantly composed of the left premotor areas (6_L) and the right primary motor area of the foot (MF_R). The remaining ROIs tend to form isolated groups.

In the Beta band both the cortical networks of the control and spinal cord injured group tend to get organized in two main modules (Clusters 1 and 2). In particular, while for both the populations the first cluster is principally composed of the cingulate...
Fig. 4. Graphical representation of the identified clusters of ROIs within the functional networks estimated from a representative control (CTRL) subject and spinal cord injured (SCI) patient during the movement preparation in the Alpha band. The functional network is illustrated as a three-dimensional graph on the realistic cortex model. Spheres located at the barycenter of each ROI represent nodes. Black directed arrows represent edges. The graph partitioning is illustrated through the nodes coloring. Nodes with same colors belong to the same cluster.

Table 1. Cortical network partitioning in the Alpha frequency band.

<table>
<thead>
<tr>
<th>CTRL</th>
<th>Cluster 1</th>
<th>Cluster 2</th>
<th>Cluster 3</th>
<th>Cluster 4</th>
<th>Cluster 5</th>
<th>Cluster 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALFA</td>
<td>CMJ, CMJ,</td>
<td>CMJ, CMJ,</td>
<td>SMJ, MLJ,</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>6J, 6J,</td>
<td>6J, 6J,</td>
<td>MLJ, MFJ,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7R</td>
<td>7R</td>
<td>MPJ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ARGI</td>
<td>CMJ, CMJ,</td>
<td>CMJ, CMJ,</td>
<td>SMJ, MLJ,</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>6J, 6J,</td>
<td>6J, 6J,</td>
<td>MLJ, MFJ,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7R</td>
<td>7R</td>
<td>MPJ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CIFE</td>
<td>CMJ, CMJ,</td>
<td>CMJ, CMJ,</td>
<td>MLJ</td>
<td>7J</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>6J, 6J,</td>
<td>6J, 6J,</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7R</td>
<td>0</td>
<td>MPJ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MADA</td>
<td>CMJ, CMJ,</td>
<td>6J, 6J,</td>
<td>SMJ, MLJ,</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>6J, 6J,</td>
<td>6J, 6J,</td>
<td>MLJ, MFJ,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7R</td>
<td>0</td>
<td>MPJ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAMA</td>
<td>CMJ, CMJ,</td>
<td>CMJ, CMJ,</td>
<td>6J, 6J,</td>
<td>7J</td>
<td>7J</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>6J, 6J,</td>
<td>6J, 6J,</td>
<td>6J, 6J,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7R</td>
<td>7R</td>
<td>MPJ</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SCI</th>
<th>Cluster 1</th>
<th>Cluster 2</th>
<th>Cluster 3</th>
<th>Cluster 4</th>
<th>Cluster 5</th>
<th>Cluster 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>BARO</td>
<td>CMJ, CMJ,</td>
<td>CMJ, CMJ,</td>
<td>SMJ, MLJ,</td>
<td>7R</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>6J, 6J,</td>
<td>6J, 6J,</td>
<td>MLJ, MFJ,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7R</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brio</td>
<td>CMJ, CMJ,</td>
<td>CMJ, CMJ,</td>
<td>SMJ, MLJ,</td>
<td>6J</td>
<td>6J</td>
<td>7J</td>
</tr>
<tr>
<td></td>
<td>6J, 6J,</td>
<td>6J, 6J,</td>
<td>MLJ, MFJ,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>MPJ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MASI</td>
<td>CMJ, CMJ,</td>
<td>CMJ, CMJ,</td>
<td>SMJ, MLJ,</td>
<td>6J, 6J,</td>
<td>7J</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>6J, 6J,</td>
<td>6J, 6J,</td>
<td>MLJ, MFJ,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7R</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>POAL</td>
<td>CMJ, CMJ,</td>
<td>CMJ, CMJ,</td>
<td>SMJ, MLJ,</td>
<td>6J</td>
<td>6J</td>
<td>7J</td>
</tr>
<tr>
<td></td>
<td>6J, 6J,</td>
<td>6J, 6J,</td>
<td>MLJ, MFJ,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7R</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRDA</td>
<td>CMJ, CMJ,</td>
<td>CMJ, CMJ,</td>
<td>SMJ, MLJ,</td>
<td>6J</td>
<td>6J</td>
<td>7J</td>
</tr>
<tr>
<td></td>
<td>6J, 6J,</td>
<td>6J, 6J,</td>
<td>MLJ, MFJ,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7R</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
motor areas CM_L and CM_R, the SM_L and SM_R and the MF_L and MF_R, the second cluster does not present a common set of ROIs across the experimental subjects neither in the CTRL or the SCI group.

### 4. Discussion

The evaluation of the estimated cortical networks was addressed by means of a set of measures typical of complex network analysis [Boccaletti et al., 2006; Micheleoyannis et al., 2006; Stam & Reijn-veld, 2007; Hilgetag et al., 2000]. We have first computed global ($E_g$) and local efficiency ($E_l$), two measures that allow characterizing the organization of the functional flows in both the inspected populations [De Vico Fallani et al., 2007b]. The results indicate that spinal cord injuries significantly ($p < 0.05$) affect only the local properties of the functional architecture of the cortical network in the movement preparation. The global property of long-range integration between the ROIs within the network did not differ significantly ($p > 0.05$) from the healthy behavior. The higher average value of local efficiency in the SCI group suggests a larger level of the internal organization and a higher tendency to form modules. In particular, this difference can be observed in the two frequency bands Alpha (7–12 Hz) and Beta (13–29 Hz) that are already known for their involvement in electrophysiological phenomena related to the preparation and to the execution of limb movements [Pfurtscher & Lopes da Silva, 1999]. Although the efficiency indexes describe the network topology concisely, they are not able to give information about the number of modules and their composition within the network. For this reason, the detection of community structures was addressed by means of the Markov Clustering (MCL) algorithm [Van Dongen, 2000; Enright et al., 2002]. The same method has already been used successfully to detect clusters in sequence similarity networks [Enright et al., 2002] and in configuration space networks derived from free-energy landscapes [Gellert et al., 2007]. The obtained results reveal a different average number of clusters for the functional networks of the
spinal cord injured patients and the control subjects in both the main spectral contents. In particular, in the Alpha band the SCI network presents an average number of modules equal to five, while the CTRL network appears to be divided into three groups. This outcome is in accordance with the significant (p < 0.05) higher level of local-efficiency found in the functional networks of the SCI patients with respect to the control subjects. A high $E_l$ value reflects a high clustering index $C$ and therefore a high density of network communities. The cortical areas of the control subjects do not present a clear partitioning in different modules. They rather appear to belong to a unique community, meaning that they are all involved, in the same way, in the exchange of information during the movement preparation. The analysis of the functional communities within the networks obtained for the spinal cord patients revealed a higher tendency to form separate clusters. The premotor areas (Brodmann 6JL and 6JR), the associative regions (Brodmann 7JL and 7JR) and the right primary motor area of the foot (MF-R) break away from the large module that was found in the networks of the CTRL group. In particular, the area MF-R and the region 6JL belong to the same cluster in at least three experimental patients. This result reveals the necessity of the SCI networks to hold a more efficient communication between these frontal premotor and primary motor structures, which are already known to be active during the successful execution of a simple movement [Ohara et al., 2001]. In the Beta band, the average number of identified clusters in the SCI networks and in the CTRL networks is less different. Moreover, the ROIs that appeared to belong to different clusters in the Alpha band are in this case functionally tied in the same community. In summary, while in the Alpha band the control group mostly presented a unique large cluster; the spinal cord injured patients mainly exhibited two clusters. These two largest communities are mainly composed of the cingulate motor areas with the supplementary motor areas and of the premotor areas with the right primary motor area of the foot. This functional separation is thought to be responsible for the highest level of internal organization in the estimated networks and strengthens the hypothesis of a compensative mechanism due to the partial alteration in the primary motor areas because of the effects of the spinal cord injury [De Vico Fallani et al., 2007a].

Acknowledgments

The present study was performed with the support of the COST EU project NEUROMATH (BMB 0601), of the Minister for Foreign Affairs, Division for the Scientific and Technologic Development, in the framework of a bilateral project between Italy and China (Tsinghua University). This paper only reflects the author’ views and funding agencies are not liable for any use that may be made of the information contained herein.

Notes

In the current work, all the estimated functional networks are treated as unweighted and directed graphs. They all have the same number of connections representing the 25% (for the community structure analysis) and the 30% (for the efficiency indexes analysis) most powerful links within the network. These particular values belonged to an interval of thresholds (from 0.1 to 0.5), for which results remained significantly stable [De Vico Fallani et al., 2007a].

References


Bartolomei, F., Boesa, I., Klein, M., Baayen, J. C., Reijnveld, J. C., Postma, T. J., Heimans, J. J., van Dijk, C.


primary sensorimotor areas during voluntary movements.’’ J. Neurosci. 21, 9377–9386.