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Linear and nonlinear analysis of brain dynamics in children with cerebral palsy

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ABSTRACT

This study was carried out to determine linear and nonlinear changes of brain dynamics and their relationships with the motor dysfunctions in CP children. For this purpose power of EEG frequency bands (as a linear analysis) and EEG fractality (as a nonlinear analysis) were computed in eyes-closed resting state and statistically compared between 26 CP and 26 normal children. Based on these characteristics accuracy of the classification between the two groups was obtained by enhanced probabilistic neural network (EPNN). Severity of gross motor and manual disabilities was determined by standard systems and the relation between the deficient brain dynamics and severity of the motor dysfunctions was obtained by Pearson's correlation coefficient. A definitely higher delta and lower theta and alpha powers, and higher EEG complexity in CP patients. As such a high accuracy of 94.8% in distinguishing the two groups was obtained. Moreover significant positive correlations were found between beta power and severity of manual disabilities and gross motor dysfunctions in the boys with CP. It is concluded that the obtained brain dynamics' characteristics are useful in diagnosis of CP. Furthermore severity of the motor dysfunctions in boys with CP could be evaluated by the beta activity.

1. Introduction

Cerebral palsy (CP) describes a vast group of childhood non-progressive developmental disorders of movement and posture (e.g. hemiplegia, spastic diplegia, spastic quadriplegia, dyskinesia, and ataxia) (Kesar et al., 2012; Koman, Smith, & Shilt, 2004; Riquelme & Montoya, 2010). Moreover often it has comorbidity with psychological problems and functional disabilities in childhood, adolescence and adulthood and severely affects social life of the CP patients (Krakovsky, Huth, Lin, & Levin, 2007; Lauruschkus, Westbom, Hallstrom, Wagner, & Nordmark, 2013; Smits et al., 2011) and their family (Guyard et al., 2012). CP occurs in around 2–4 per 1000 live births (Bax, Tydeman, & Flodmark, 2006; Kirby et al., 2011). It is caused by a lesion of the cerebral motor cortex occurring in utero, during or after birth (Koman et al., 2004).

Traditionally, diagnosis of CP and monitoring the effectiveness of therapeutic procedures related to it have been very subjective, complicated, and time-consuming, including comprehensive history taking, physical testing, and assessment of secondary problems (Fairhurst, 2012; Koman et al., 2004). Nowadays, neuroimaging tools are increasingly used in investigation of the neuropathology, and deficient brain dynamics, and also the objectification of diagnosis in many

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neuropsychiatric and neurologic disorders. However, to the authors' knowledge there are only a few neuroimaging-based studies conducted on CP as are shortly presented in the following literature review. Bax et al., 2006 reported various MRI patterns of deficit in CP children primarily including white matter damage of immaturity (42%), basal ganglia damage (12%), malformation (9%), and cortical–subcortical damage (9%). Some other fMRI studies have shown that reduced sensory perception and somatosensory processing deficits in CP patients may be related to the deficits in the somatosensory and parietal cortex (Coq et al., 2008; Wingert, Sinclair, Dixit, Damiano, & Burton, 2010). Burton, Dixit, Litkowski and Wingert (2009) through functional connectivity analysis of the resting state MRI data showed that participants with spastic diplegia had significantly expanded networks for the somatosensory and motor regions comparing with the healthy participants. Comparing resting EEGs of children with spastic diplegia with those of normal children, Kulak and Sobaniec (2003) reported increased delta and theta powers in almost all brain loci and decreased alpha power in the occipital loci. Kulak and Sobaniec (2005) and Kulak, Sobaniec and Bockowski (2005) reported lower inter-hemispheric and higher right intra-hemispheric synchronizations at the alpha EEG band in children with hemiparetic cerebral palsy compared to normal children. Kurz and Wilson (2011) showed that neuromagnetic activity of somatosensory cortices representing the foot in CP children is diminished. Guo et al. (2012) in an MEG study reported extensive high-gamma oscillations in the somatosensory cortex of children with CP. Lee et al. (2012) using a new EEG brain mapping system examined the alpha band (8–12 Hz) power spectra of a small sample size of participants (5 healthy children and 7 children with CP) in discrimination of the healthy and CP children and reported the successfulness of the method.

Regarding the scarcity of neuroimaging-based studies conducted on CP patients with the objective of diagnosis or investigation of electrophysiological abnormalities, this paper reports an attempt for identifying changes of brain dynamics in CP children with the aim of reaching diagnostic-aiding and monitoring-aiding tools for helping the CP children. As the brain is a highly complex and nonlinear system (Ahmadlou & Adeli, 2011a,b; Stam, 2005), analysis of the brain using only traditional linear methods like power spectrum cannot reveal all the characteristics of brain dynamics (Ahmadlou, Ahmadi, Rezazade, & Azad-Marzabadi, 2013; Mamashli, Ahmadlu, Golpayegani, & Gharibzadeh, 2010). Therefore in this paper the authors compare both linear and nonlinear characteristics of brain dynamics between children with and without CP. As such, power spectrum analysis of EEG frequency bands as a linear analysis method and computation of EEG complexity as a key characteristic of nonlinear dynamics (Ahmadi, Ahmadlou, Rezazade, Azad-Marzabadi, & Sajedi, 2013) are compared between CP and normal children, in the resting-state. Statistical analysis is utilized to evaluate the EEG power and complexity differences between the two groups. Then in order to show how useful the approach could be in practical diagnosis of CP, using an artificial neural network the data are classified to the two groups.

2. Materials and methods

2.1. Participants

The participants of this study included 26 spastic CP patients aged from 4 to 14 years (13 females) and 26 age- and sex-matched healthy participants. The children in the case group were recruited between Jan-October 2012 from those attending rehabilitation Clinics affiliated with the University of Social Welfare and Rehabilitation Sciences (USWR) in Tehran, Iran. The healthy children were randomly selected from 4 pre-schools and schools located at four different parts of the city, as the control group. The healthy participants included in the study had to have no history of neurological/psychological disorders, brain injuries or seizures. The patients were spastic CP (15 diplegic and 11 quadriplegic) that had IQ score $\geq$70 on the basis of Raven's Standard Progressive Matrices (Raven, 2000) and had to have no history of brain seizure and epilepsy in their history. The etiologies of cp were prematurity and low birth-weight in the 11 diplegic, hypoxic-ischemic encephalopathy in the 11 quadriplegic and prenatal problems (maternal diseases) in the 4 other diplegic patients. The study had the approval of the ethic committee of the USWR. Participants' anonymity and confidentiality were assured. Participants were informed of their right to refuse consent and of their right to withdraw consent or discontinue participation at any time without penalty. The parents of all participants signed a written informed consent prior to participation. A demographic information form was completed by parents of the participants for demographic characteristics.

The severity of gross motor disability was determined with the Gross Motor Function Classification System (GMFCS) tool (Palisano, Rosenbaum, Walter, Russell, Wood, & Galuppi, 1997; Palisano, Rosenbaum, Bartlett, & Livingston, 2008), by an occupational therapist. The GMFCS is a 5 level classification system that measures 5 gross motor functions of CP children [(a) lying & rolling, (b) sitting, (c) crawling and kneeling, (d) standing, (e) walking, running and jumping]. Children who have motor problems similar to those classified in "Level I" can generally walk without restrictions but tend to be limited in some of the more advanced motor skills. Children whose motor function has been classified at "Level V" are generally very limited in their ability to move themselves around even with the use of assistive technology (Palisano et al., 2008; Rosenbaum et al., 2002; Sentenac et al., 2013; Tseng, Chen, Shieh, Lu, & Huang, 2011).

The severity of manual disabilities of children with CP were assessed and classified by the Manual Ability Classification System (MACS) (Elissson et al., 2006). MACS can be used for children aged 4–18 years. It describes how children with CP use their hands to handle objects in daily activities. MACS describes five levels. The levels are based on the children's self-initiated ability to handle objects and their need for assistance or adaptation to perform manual activities in everyday life. Level I includes children with minor limitations, while children with severe functional limitations will usually be found at levels IV and V. The five levels in MACS form an ordinal scale, which means that the levels are 'ordered' but differences