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The influence of central neuropathic pain in paraplegic patients on performance of a motor imagery based Brain Computer Interface ☆

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HIGHLIGHTS

- Motor imagery based BCI-classifier built on EEG data of paraplegic patients, gives higher classification accuracy in patients with central neuropathic pain compared to patients with no chronic pain.
- Higher BCI classification accuracy in paraplegic patients with central neuropathic pain is accompanied with stronger event related desynchronisation during motor imagery.
- BCI classification accuracy between feet and a hand was comparable with classification accuracy between hands, in all three groups of participants.

ABSTRACT

Objective: The aim of this study was to test how the presence of central neuropathic pain (CNP) influences the performance of a motor imagery based Brain Computer Interface (BCI).
Methods: In this electroencephalography (EEG) based study, we tested BCI classification accuracy and analysed event related desynchronisation (ERD) in 3 groups of volunteers during imagined movements of their arms and legs. The groups comprised of nine able-bodied people, ten paraplegic patients with CNP (lower abdomen and legs) and nine paraplegic patients without CNP. We tested two types of classifiers: a 3 channel bipolar montage and classifiers based on common spatial patterns (CSPs), with varying number of channels and CSPs.
Results: Paraplegic patients with CNP achieved higher classification accuracy and had stronger ERD than paraplegic patients with no pain for all classifier configurations. Highest 2-class classification accuracy was achieved for CSP classifier covering wider cortical area: 82 ± 7% for patients with CNP, 82 ± 4% for able-bodied and 78 ± 5% for patients with no pain.
Conclusion: Presence of CNP improves BCI classification accuracy due to stronger and more distinct ERD.
Significance: Results of the study show that CNP is an important confounding factor influencing the performance of motor imagery based BCI based on ERD.

1. Introduction

Spinal cord injury may cause paralysis leaving a person highly dependent on their caregivers for most basic activities of daily living (Field-Fotte, 2009). Therefore various assistive devices have been used to improve patients' independence and quality of life (Poduri and Cesarz, 2009). In the recent years, assistive and rehabilitation devices based on Brain Computer Interface (BCI) have been intensively explored, due to their capacity to promote combined neurological and physical recovery (Dobkin, 2007; Roset et al., 2013).

Motor imagery (MI) has been a frequently used BCI strategy which can be applied for controlling assistive devices (Pfurtscheller et al., 2000; Kauhanen et al., 2006; Leeb et al.,

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2007) and for rehabilitation of SCI patients with incomplete injury and stroke, that have partially preserved movements (Roset et al., 2013; Pfurtscheller et al., 2009; Daly et al., 2009; Tam et al., 2011; Onose et al., 2012). However, there are two major challenges in using MI-BCI in SCI patients: reduced brain activity and reorganisation of somatosensory-cortex (Kokotilo et al., 2009); both affecting the BCI performance. Several BCI studies (Pfurtscheller et al., 2000, 2009) showed that compared to the able-bodied, SCI patients have distinctive activation patters and reduced event related desynchronisation during MI causing poor performance of a BCI classifier. Multiple imaging studies demonstrated the reorganisation of the sensory-motor cortex, causing the posterior shift of the maximum activity and modification of the level of cortical activity during imagined or attempted movements (Green et al., 1999; Tran et al., 2004; Kokotilo et al., 2009; Jurkiewicz et al., 2010; Vuckovic et al., 2014).

Within the BCI community it is widely accepted that the main cause of these changes is a disuse reorganisation of the cortex caused by paralysis (Kauhanen et al., 2006; Pfurtscheller et al., 2009). Although paralysis is the most obvious effect of the injury, SCI is a complex injury with multiple primary and secondary consequences (Field-Fotte, 2009). It is therefore possible that some secondary consequences of SCI which contribute to the reorganisation of the cortex also affect performance of MI based BCI. One of the most frequent secondary consequences of SCI is chronic pain. A very common subtype of the chronic pain, severely affecting around 40% of SCI population, is central neuropathic pain (CNP) (Siddall et al., 2003; Watson, 2008). CNP is caused by an injury to the somato-sensory system (Haanpaa et al., 2011) but can appear months or years post-injury. An explanation for the origin of CNP is the thalamo-cortical dysrhythmia following the injury (Sarnthein and Jeanmonod, 2008), suggesting that CNP is generated in the brain rather than in the body (Apkarian et al., 2009; Haanpaa et al., 2011; Henderson et al., 2013). Although the origin of CNP is within the central nervous system, it is perceived as coming from the paralysed limbs (Haanpaa et al., 2011). In SCI patients CNP is manifested as a chronic pain below the level of the injury, described as burning, tingling stabbing, shooting or aching sensation (Siddall et al., 2003; Baastrup and Finnerup, 2008). A thermosensory inhibition hypothesis (Craig, 2002), explains CNP as a thermoregulatory dysfunction, that is further supported by a burning sensations, often reported by patients with CNP.

CNP equally affects patients with complete and with incomplete SCI injury (Siddall et al., 2003). It also affects other groups of potential BCI users like stroke patients (8%) (Andersen et al., 1995) and is very frequent in amputees (80%) (Flor, 2002), patients with multiple sclerosis (27%) (Osterberg et al., 2005) and Parkinson's disease (10%) (Beiske et al., 2009).

Evidence for correlation between CNP and reorganisation of the sensorimotor cortex has been shown by many studies (Flor, 2002; Gustin et al., 2010a; Wrigley et al., 2009) where, due to sensory loss caused by the injury, the affected cortical somatotopy undergoes re-mapping or reorganisation, proportional to the intensity of pain. On the contrary, Makin et al. (2013) showed that in persons who suffer from CNP due to amputation, the sensory-motor cortex undergoes less reorganisation than in amputees with no pain. This result indicates that it is possible to distinguish between the effects of sensory loss and pain initiated by trauma leading to sensory loss.

While the areas of the brain involved in processing of pain normally do not involve the primary motor cortex (Apkarian et al., 2009; Jensen, 2010), fMRI studies demonstrated that the presence of CNP in SCI patients causes an increased activation of the primary motor cortex during imagination of movements (Gustin et al., 2010a; Wrigley et al., 2009). EEG studies of spontaneous brain activity also showed the increased power of the theta band and a shift of the dominant alpha peak frequency towards the theta band in paraplegic and other groups of patients suffering from CNP (Boord et al., 2008; Sarnthein et al., 2006; Stern et al., 2006; Jensen et al., 2013; Vuckovic et al., 2014). Evidence of correlation between CNP and the level of the brain activity has been shown in our previous study (Vuckovic et al., 2014): we defined spontaneous and dynamic EEG signatures of CNP by comparing responses of paraplegic patients with CNP, paraplegic patients with no CNP and able-bodied people in relaxed state and during cue-based MI task. Results of that study showed that patients with CNP had strongest and spatially distinctive event related desynchronisation (ERD) during MI in the theta, alpha and beta frequency bands, with maximum activity shifted posteriorly. Theta band desynchronisation during motor imagination was a singular feature of patients with CNP. Patients with no CNP had weakest ERD, that has spatial topography comparable to those of the able-bodied group.

Given the previously mentioned evidence regarding the role of CNP, there is a possibility that performances of a MI-based BCI, which uses ERD based features, may not only vary between paralysed and able bodied people, but importantly between paralysed people with and without CNP. It should be noted that in previous reports (Gustin et al., 2008, 2010b) the effect of motor imagery on CNP was not analysed for the purpose of BCI, so the effect of CNP on BCI performance is unknown. From a BCI perspective increased cortical activity during MI in patients with CNP is a desirable feature as it implies that better classification accuracy might be achieved. However, a study on SCI patients with CNP who practiced motor imagery for several weeks showed that prolonged imagination of movements of a painful part of the body worsens pain, i.e. MI is able to produce painful sensation without a peripheral input (Gustin et al., 2008, 2010b). Equally important is to question whether MI as practiced for BCI has an adverse effect on CNP.

The aim of this EEG-based study was to test whether the presence of CNP in paraplegic patients influences the performance of MI based BCI. We compared performances of BCI classifiers and the accompanying ERS/ERD responses between three groups: able bodied people, paraplegic patients with no pain and paraplegic patients with CNP. These results are potentially also relevant for other patient groups suffering from CNP, e.g. stroke patients, who are typical BCI candidates.

2. Methods

2.1. Participants

Three groups of age-matched adults (age between 18 and 55) were recruited. The groups were:

1. Ten paraplegic patients (3F, 7M age 46.2 ± 9.4), with diagnosed CNP below the level of injury, referred to as Patients With Pain (PWP),
2. Nine paraplegic patients with no chronic pain (2F, 7M age 43.8 ± 9.1), referred to as Patients with No Pain (PNP),
3. Nine able bodied volunteers with no chronic pain (3F, 6M age 39.6 ± 10.2) referred to as Able Bodied (AB).

The neurological level of SCI was determined using the American Spinal Injury Association (ASIA) impairment classification (·Marino et al., 2003). Injury level A means the loss of motor and sensory functions while level B means the loss of motor function with some sensations preserved. All SCI patients were at least 1 year post injury and had a spinal lesion at or below T1. The inclusion criteria for patients with CNP was a positive diagnosis of CNP, reported pain level $\geqslant 5$ on the Visual Numerical Scale (VNS ranging from 0 to 10, 0 meaning no pain and 10 meaning worst pain imaginable) and a treatment history of CNP for at least 6 months. The

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