NeuroImage 85 (2014) 451–460

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/ynimg

A semi-immersive virtual reality incremental swing balance task activates prefrontal cortex: A functional near-infrared spectroscopy study

Sara Basso Moro [a], Silvia Bisconti [a], Makii Muthalib [b], Matteo Spezialetti [a], Simone Cutini [c], Marco Ferrari [a],*, Giuseppe Placidi [a], Valentina Quaresima [a]

[a] Department of Life, Health and Environmental Sciences, University of L'Aquila, Via Vetoio, 67100 L'Aquila, Italy
[b] Movement to Health, University of Montpellier 1. Euromov, 700 Avenue du Pic Saint Loup, 34090 Montpellier, France
[c] Department of General Psychology, University of Padua, Via Venezia 8, Padova 35131, Italy

ARTICLE INFO

Article history:
Accepted 3 May 2013
Available online 17 May 2013

Keywords:
Swing balance task
Cortical oxygenation
Functional near-infrared spectroscopy
Prefrontal cortex
Virtual reality

ABSTRACT

Previous functional near-infrared spectroscopy (fNIRS) studies indicated that the prefrontal cortex (PFC) is involved in the maintenance of the postural balance after external perturbations. So far, no studies have been conducted to investigate the PFC hemodynamic response to virtual reality (VR) tasks that could be adopted in the field of functional neurorehabilitation. The aim of this fNIRS study was to assess PFC oxygenation response during an incremental and a control swing balance task (ISBT and CSBT, respectively) in a semi-immersive VR environment driven by a depth-sensing camera. It was hypothesized that: i) the PFC would be bilaterally activated in response to the increase of the ISBT difficulty, as this cortical region is involved in the allocation of attentional resources to maintain postural control; and ii) the PFC activation would be greater in the right than in the left hemisphere considering its dominance for visual control of body balance. To verify these hypotheses, 16 healthy male subjects were requested to stand barefoot while watching a 3 dimensional virtual representation of themselves projected onto a screen. They were asked to maintain their equilibrium on a virtual blue swing board susceptible to external destabilizing perturbations (i.e., randomizing the forward-backward direction of the impressed pulse force) during a 3-min ISBT (performed at four levels of difficulty) or during a 3-min CSBT (performed constantly at the lowest level of difficulty of the ISBT). The center of mass (COM), at each frame, was calculated and projected on the floor. When the subjects were unable to maintain the COM over the board, this became red (error). After each error, the time required to bring back the COM on the board was calculated (returning time). An eight-channel continuous wave fNIRS system was employed for measuring oxygenation changes (oxygenated-hemoglobin, O_2Hb; deoxygenated-hemoglobin, HHb) related to the PFC activation (Brodmann Areas 10, 11 and 46). The results have indicated that the errors increased between the first and the second level of difficulty of the ISBT, then decreased and remained constant; the returning time progressively increased during the first three levels of difficulty and then remained constant. During the CSBT, the errors and the returning time did not change. In the ISBT, the increase of the first three levels of difficulty was accompanied by a progressive increase in PFC O_2Hb and a less consistent decrease in HHb. A tendency to plateau was observable for PFC O_2Hb and HHb changes in the fourth level of difficulty of the ISBT, which could be partly explained by a learning effect. A right hemispheric lateralization was not found. A lower amplitude of increase in O_2Hb and decrease in HHb was found in the PFC in response to the CSBT with respect to the ISBT. This study has demonstrated that the oxygenation increased over the PFC while performing an ISBT in a semi-immersive VR environment. These data reinforce the involvement of the PFC in attention-demanding balance tasks. Considering the adaptability of this virtual balance task to specific neurological disorders, the absence of motion sensing devices, and the motivating/safe semi-immersive VR environment, the ISBT adopted in this study could be considered valuable for diagnostic testing and for assessing the effectiveness of functional neurorehabilitation.

Abbreviations: fNIRS, functional near infrared spectroscopy; PFC, prefrontal cortex; ISBT, incremental swing balance task; CSBT, control swing balance task; COM, center of mass; O_2Hb, oxygenated hemoglobin; HHb, deoxygenated hemoglobin; VR, virtual reality; PI, postural instability; COP, center of pressure; fMRI, functional magnetic resonance; EEG, electroencephalography; SBT, swing balance task; ICBM, International Consortium for Brain Mapping; BAs, Brodmann Areas; HR, heart rate; 3D, 3 dimensional; STAI, State-Trait Anxiety Inventory; LI, laterality index.

* Corresponding author. Fax: +39 0862 433785.
E-mail address: marco.ferrari@univaq.it (M. Ferrari).

1053-8119/$ – see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.neuroimage.2013.05.031

Introduction

Postural instability (PI) and falls are common in old people and in brain damaged patients suffering from motor disabilities (e.g., Parkinson's disease and stroke), and often result in injuries or hospitalization, which can significantly impair the quality of life of these individuals. More specifically, PI consists of alterations in postural control strategies (i.e., changes in both anticipatory feedforward, and compensatory feedback postural reactions) during standing balance tasks; such anomalies may occur either when responding to an unexpected destabilizing perturbation or when performing voluntary destabilizing movements. To date, the functional neural correlates underlying standing balance control and PI are not well known. Standing balance control is a complex sensorimotor action based on automated and reflexive spinal programs under the influence of several distinct and separate supra-spinal centers in the brainstem, cerebellum and cortex (Drew et al., 2004). Concerning the evaluation of standing balance, systems based on force platforms are currently the standard, since they enable to estimate the center of pressure (COP) and the center of mass (COM) distribution by means of pressure sensors in the force platform (Winter, 1995). The ability to voluntarily move the body to positions within the limits of stability is fundamental to mobility tasks such as reaching for objects, transitioning from a seated to a standing position, and walking. The assessment and rehabilitation of standing balance control require a multidisciplinary approach that could maximize functional recovery with the aid of new technologies, such as virtual reality (VR).

In the last few years, there has been increasing research interest in the application of VR technology for neurorehabilitation. In contrast with traditional rehabilitation procedures, which may be tedious, resource-intensive and expensive, VR provides opportunities to engage in enjoyable and purposeful tasks. Recently, the neural correlates of VR experiences have been investigated by neuroimaging techniques (Bohil et al., 2011; Seraglia et al., 2011). The most widely used neuroimaging modalities are functional magnetic resonance imaging (fMRI) (Bandettini, 2007), electroencephalography (EEG) (Kober et al., 2012), and functional near-infrared spectroscopy (fNIRS) (Ferrari and Quaresima, 2012). However, if compared with the other methods, fNIRS represents an optimal cortical imaging monitoring tool to evaluate the patient's motor performance in a VR environment (Holper et al., 2010), given that it does not require stringent physical and motor constraints. fNIRS is a non-invasive neuroimaging technology that measures concentration changes of oxygenated-hemoglobin (O_2Hb) and deoxygenated-hemoglobin (HHb) in cerebral microcirculation blood vessels by means of the characteristic absorption spectra of hemoglobin in the near-infrared range. Cerebral blood flow adequate for brain activity and metabolic demand is maintained through the processes of autoregulation and neurovascular coupling. Coupling between neuronal activity and blood flow is fundamental to brain function. When a specific brain region is activated, cerebral blood flow increases in a temporally and spatially coordinated manner tightly linked to changes in neural activity through a complex sequence of coordinated events involving neurons, glia, arteries/arterioles, and signaling molecules (Kleinfeld et al., 2011). fNIRS, a vascular-based functional brain imaging technique, relies on this coupling to infer changes in neural activity that is mirrored by changes in blood oxygenation in the region of the activated cortical area (i.e., the increase in O_2Hb and the decrease in HHb).

fNIRS has been applied for evaluating the cortical activation during motor tasks as hand grasping (see Leff et al., 2011 for a review), walking (Atsumori et al., 2010; Miyai et al., 2001), stepping (Huppert et al., 2012), and real-world activities realized in a computer simulated artificial environment (Ayaz et al., 2011; Karim et al., 2012; Tachibana et al., 2011). Different cortical areas were found involved in these artificial environment tasks; in particular parietal and temporal cortices were found activated in response to a multimodal dance video game (Tachibana et al., 2011), the prefrontal cortex (PFC) was found activated during spatial navigation learning in virtual mazes (Ayaz et al., 2011), and temporal cortex was found activated during a balance task associated to a video game (Nintendo Wii, Nintendo Co. Ltd, Japan) simulating downhill skiing (Karim et al., 2012). Moreover, fNIRS studies have highlighted the involvement of the PFC and other cortical regions in maintaining postural balance after external perturbation in healthy subjects and patients recovering from stroke (Mihara et al., 2008, 2012). EEG imaging techniques have also emphasized the importance of the fronto-central region for the regulation of the postural equilibrium of standing subjects voluntarily moving continuously in the forward and backward direction (Slobounov et al., 2005, 2008).

So far, no studies have been conducted for investigating the cortical hemodynamic response to VR tasks that could be adopted in the field of functional neurorehabiliation. Moreover, it has been argued that cognitive decline (particularly related to executive functioning) might be a contributing factor to PI and falls: such failure of executive control has been suggested to be associated with changes in the PFC activation (Anstey et al., 2009). However, the relation between changes in the PFC activation and the PI has not yet well understood. It has been reported that the ability to integrate visual and proprioceptive information is required to adaptively modify the postural stability in response to changes of the VR environment and to perform the goal of action (Sober and Sabes, 2003). Moreover, a hemispheric asymmetry in the visual contribution to postural control has been shown in healthy adults, revealing a greater right hemispheric involvement (Pérennou et al., 1997). Previous fNIRS studies have indicated that the PFC is involved in the maintenance of postural control after external perturbations via the allocation of the attention (Mihara et al., 2008, 2012).

The present study was aimed at assessing by fNIRS the PFC hemodynamic response to a swing balance task (SBT), performed either at constant (control swing balance task —CSBT) or incremental (incremental swing balance task — ISBT) difficulty, in a semi-immersive VR environment driven by a depth-sensing camera. During the SBT, the control of the equilibrium over a virtual swing board, by forward-backward postural sways induced by the task, was required. Considering the: 1) PFC involvement in the allocation of the attentional resources to maintain postural control, and 2) the right hemisphere dominance for visual control of body balance, we hypothesized that the PFC would be activated bilaterally by the increase of difficulty of the SBT, and this PFC activation would be greater in the right hemisphere.

Methods

Subjects

Sixteen right-handed healthy male volunteers (mean age: 29.0 ± 4.8 y.; body mass index: 24.0 ± 2.6 kg/m^2) without self-reported balance or mobility disorders participated in the study. Only men were recruited to avoid whichever gender differences in emotional responses. Informed consent was obtained after a full explanation of the protocol and the non-invasiveness of the study. To exclude left-handed subjects, all participants completed the Edinburgh Handedness Inventory (Oldfield, 1971) assessing hand dominance.

Experimental setup

fNIRS instrumentation

An eight-channel fNIRS system (NIRO-200 with the multifiber adapter, Hamamatsu Photonics, Japan) was used to measure changes in O_2Hb and HHb over the PFC area. Two optical fiber bundles (length: 2.5 m; diameter: 3 mm) carried the light to the left and the right PFC, whereas eight optical fiber bundles of the same size (four for each hemisphere) collected the light emerging from the same cortical areas. The illuminating and collecting bundles were assembled into a specifically designed flexible probe holder (Elastomer LCG20R, Chiorino S.p.A, Italy) ensuring that the position of the 10 optodes,