A virtual ball task driven by forearm movements for neuro-rehabilitation

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***Abstract*—The present study was aimed at describing a semi-immersive virtual reality environment, driven by a 3D hand sensing device (LEAP Motion Controller), to define a virtual task based on a virtual ball moving on a virtual path. The prefrontal cortex haemodynamic responses during the execution of this demanding task were evaluated by a 16-channel functional near-infrared spectroscopy (fNIRS) system. A bilateral ventrolateral prefrontal cortex activation was found during the virtual task. Although the proposed task has not been yet applied in the neuro-rehabilitation field, it has the potential to be adopted in the upper limb functional assessment and rehabilitation treatment.**

***Keywords*— virtual reality, functional near-infrared spectroscopy, LEAP Motion Controller, neuro-rehabilitation, prefrontal cortex.**

I. Introduction

Virtual reality (VR) is a computer-based technology that allows the interaction between users and multisensory simulated environments and the receipt of the "real-time" feedback on performance. Different advantages can be obtained by the application of the VR in rehabilitation. In particular, virtual environments are interactive, flexible and customizable for different rehabilitation requirements, and continuous on-line or off-line feedbacks of the obtained performance can be provided and used to adjust the following rehabilitation sessions. Novel strategies targeting motor skill development have recently emerged also using very low-cost sensing devices [1-7]. However, it is still critical to determine the underlying neurological mechanisms of the interaction within a VR environment, and to consider how they may be exploited to facilitate the sensorimotor learning and functional recovery.

The compatibility of VR systems with neuroimaging techniques, such as functional magnetic resonance imaging (fMRI), functional near-infrared spectroscopy (fNIRS) and positron emission tomography (PET), allows the investigation of these issues with multimodal stimulation, high degree of ecological validity, and control of the changes occurring in brain activity. Despite their widespread use, fMRI and PET present many disadvantages including the bulky and the high costly devices, the loud noise, the horizontal and unnatural position of the participant during the experimental session. These features are limiting factors for their use in the context of VR rehabilitation. The fNIRS technique overcomes these limitations and allows the non-invasive cortical investigation by measuring the concentration changes in oxygenated haemoglobin (O_2Hb) and deoxygenated haemoglobin (HHb) [8,9]. Considering the relatively low physical constraints required in fNIRS measurement, this neuroimaging technique could be considered an optimal candidate to be used in combination with VR based neuro-rehabilitation.

The present study was aimed at presenting the Virtual Ball Task (VBT), in a semi-immersive VR environment, driven by a 3D hand sensing device and at assessing, by fNIRS, the haemodynamic responses of the prefrontal cortex (PFC) during the VBT. It was hypothesized that the PFC would be involved in the VBT execution.

II. Materials and methods

Eight right-handed healthy male volunteers (mean age: 26.1±2.9 years; high level of education), participated in this study that was approved by the local ethics committee.

The VBT was implemented by connecting and extending two leading technologies: a 3D hand sensing device, and a high performance real time 3D engine. The 3D hand sensing device consisted of the LEAP Motion Controller [10] that provided both a 3D hand model and the real-time hand tracking information for enabling subjects to transpose their hand movements within a virtual 3D task. Note that the LEAP Motion Controller was designed to allow a freehand natural interaction. The device was used to capture the movements of the hand (Fig. 1, left side) and to join these movements to a set of commands to drive a virtual ball (VB) within a virtual environment (Fig. 1, right side). The Torque 3D Engine (www.garagegames.com), a cross-platform high performance real time 3D engine, allowed both the editing and the rendering of the whole virtual 3D game. By using the aforementioned technologies, a controllable VB and virtual path (VP) were created by using a customized version of Marble Motion (www.garagegames.com), a well-known game available on the web. We enriched the whole native source code in order to perform the requirements of our task. In particular, we added some additional tools: a time driven version of the task in which both start and end of the session were established by a fixed time interval; information related to the subject-game interaction process were stored (including the number and the positions of the falls in the VP; the time necessary to the subject to conclude the task; the followed trajectory, speed, and acceleration of the VB). Moreover, to increase subject's concentration and motivation on the task, we redefined the whole technical items, including: elements of the VP, textures,

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and materials. The subject placed his forearm on a fixed and firm support and the center of the palm perpendicular to the LEAP device, at a distance of about 0.25 m, with all the five fingers extended. The task started with a stationary VB placed at the beginning of the VP, while the subject was maintaining his opened right hand above the device. The goal of the task was to move the VB on a VP by avoiding the falls outside the path. A twenty-channel continuous wave fNIRS system (Oxymon Mk III, Artinis Medical Systems, The Netherlands) was employed to map changes in O_2Hb and HHb over the bilateral PFC. The O_2Hb and HHb data from sixteen measurement points and from four short-separation (SS) channels were acquired at 10 Hz. In the measurement points (channels) the detector–illuminator distance was set at 3.5 cm.

The task protocol included: a 1-minute baseline, a 2-minute VBT, and a 1-minute recovery. During the baseline and the recovery period, the participants were asked to observe a white fixation cross presented on a black screen, and to relax in order to get stable baseline fNIRS signals. During the VBT, the subject had to interact with the VB, guiding it over the VP through four hand movements starting from the wrist (Fig. 1). When the VB fell outside the VP or/and when the subject reached the end of the VP before the predefined 2-minute VBT, the VBT started again from the beginning.

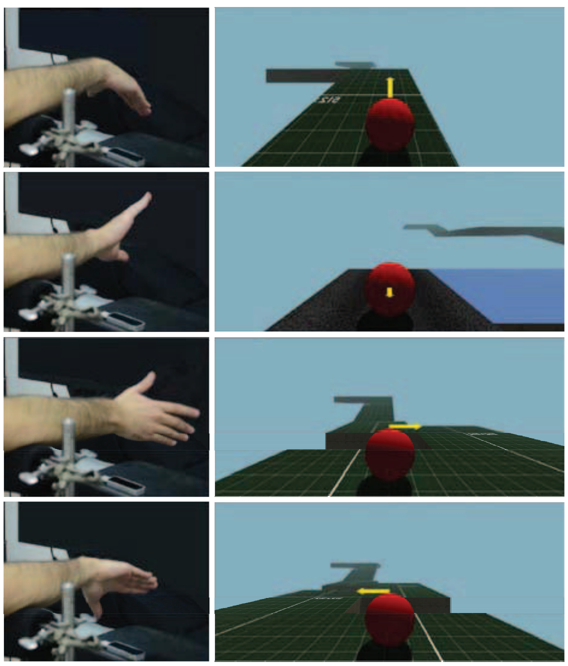

Fig. 1. Left side, from top to bottom, the four hand movements (wrist flexion to allow the ball to proceed forward; wrist extension to allow the ball to decrease the speed (up to stop) and to proceed backward; forearm supination and rotation to drive the ball to the right or to the left) are shown. In the right side, from top to bottom the VB over the path, driven by the corresponding hand movements (in the direction indicated by the yellow arrow), are shown.

III. Results and discussion

The number of falls and the completed paths were 2.0±1.2 (range 0-3) and 1.2±0.9 (range 0-2), respectively. These values indicate the heterogeneous difficulty faced by the subjects in the VBT execution. The fNIRS data were filtered with the Wavelet motion correction and SS signal regression to reduce physiological noise contamination [11]. The integral values of the O_2Hb/HHb concentration changes were calculated from the starting of the VBT until the end of each VBT. These values have been corrected for the baseline period.

Only the bilateral ventrolateral PFC (VLPFC) was found activated (O_2Hb increase coupled with HHb decrease) during the execution of the VBT. This activation was not affected by the increase of the task difficulty obtained by changing the mass of the VB. The fact that the bilateral VLPFC was mainly involved in the VBT could be explained by the VLPFC specific role in using the visual context to generate goals.

In conclusion, to the best of our knowledge, this is the first time in which fNIRS has been employed to investigate the PFC response to a VBT (driven by forearm movements) performed in a semi-immersive VR environment. The present study highlights the potential advantages offered by a semi-immersive VR based neuro-rehabilitation system, as confirmed by fNIRS assessment of the PFC activation. In contrast with traditional rehabilitation procedures, which may be resource-intensive and expensive, VBT provides opportunities to engage in enjoyable and purposeful tasks. In addition, VBT can be used for neuro-rehabilitation in a warm and friendly atmosphere to motivate patients to follow the training without interruptions.

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