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“Walking” into freely moving brain monitoring via real-time TD-NIRS

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ABSTRACT

Thanks to recent developments in time-domain near-infrared spectroscopy (TD-NIRS), it is now possible to monitor brain activity during freely moving exercises. A wearable single-channel TD-NIRS instrument has been exploited to retrieve oxy- and deoxygenated hemoglobin absolute concentrations during gaiting experiments. It was possible to retrieve quantitative results concerning functional brain activation in the motor cortex areas, with high rejection of motion artifacts.

Keywords: wearable, compact, monitor, TD-NIRS, brain, freely-moving, oxygenation.

1. INTRODUCTION

Gaiting disfunctions are considered within the major issues in elderly population [1]. Walking-related pathologies are very frequent and represent a non-negligible cost for national healthcare systems [2]. They can eventually lead to major disabilities and are commonly related to neuronal pathologies, such as Parkinson and Alzheimer. Direct neurovascular feedback can be an effective tool to determine the severity of deambulatory disfunctions and helps monitoring the progress of related pathologies. Current brain monitoring technologies, such as functional magnetic resonance imaging (fMRI) and positron emission tomography, are commonly associated to high costs, difficult usage and bulkiness, preventing physiologists to have direct information on brain activation during freely moving walking tasks. In this work, we present a compact optical brain oximeter that can be worn as a backpack to monitor brain activity in ecological environments. We tested device capabilities, monitoring the lower limb motor cortex area of three healthy volunteers while performing a freely moving gaiting task. The system is based on time-domain near-infrared spectroscopy (TD-NIRS), this technique provides the unique feature of being able to retrieve absolute tissue optical parameters and estimate physiological variations with depth selectivity. The device performances have been previously validated by standardized characterization protocols on calibrated tissue phantoms, recently developed in European collaborative efforts (e.g. BIP, MEDPHOT, nEUROPt) [3],[4],[5].

2. MATERIALS AND METHODS

2.1 TD-NIRS compact device

The TD-NIRS device used in this work is equipped with two pulsed diode lasers working at 670 nm and 830 nm wavelengths, a time-to-digital converter (TDC) application-specific integrated circuit (ASIC) that is capable of measuring the arrival time of the photons revealed by a single-photon counting module [6]. All these sub-components, together with the controlling electronics, have been custom-made in the laboratories of Politecnico di Milano, aiming to overcome the bulkiness of standard research-grade TD-NIRS devices. The device was battery-operated and equipped

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with remote-control features (via Wi-Fi), ensuring therefore completely free motion to all the participants. More information about the system technical description can be found in [7], whereas its application and extended characterization can be found in [8].

2.2 Probe and Measuring Location

Probe positioning (Fig.1) was selected based on previous works, such as [9] in which motor imagery is used to study cortical activation in forward and backward gaiting. Brain cortex areas, close to the vertex, C1 and C2 position (electroencephalography, EEG 10/20 system mapping) are strongly involved in both tasks and the barycenter of the activated area resulted to be at a depth of approximately 2.5 cm, independently of the task [9]. All subjects were right-handed and the left hemisphere (C2 position) has been selected. The task-related activations comprise also more superficial layers of the primary motor cortex (PM1) and supplementary motor areas (SMA), we are therefore confident that the brain region of interest are within TD-NIRS device's monitoring capabilities [10]. The optical probe was secured on the scalp of the participants with a black elastic bandage around the head, avoiding ears and eyes coverage. The distance between the injection and the detection points was set to 30 mm to ensure sufficient signal-to-noise-ratio. The optode was custom-made for brain measurements. It was 3D-printed exploiting filament deposition additive manufacturing technique of a biodegradable black polylactic acid material. The probe was less than 10 mm thick and light beams were 90° bent via highly reflective optical components, to ensure normal incidence on the scalp and comfortable fiber management.

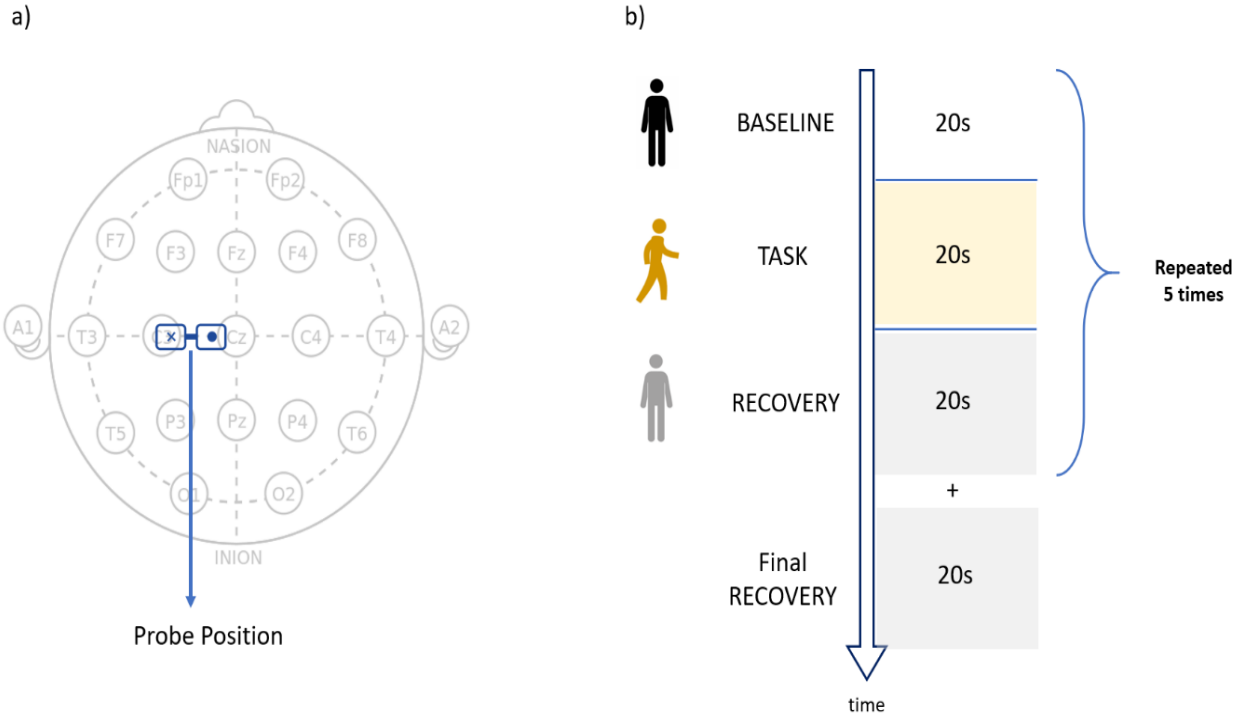

Figure 1 a) Sketch of the probe positioning (EEG 10/20 system mapping) and b) sketch of the experimental protocol. The same protocol here depicted has been repeated three times: forward walking task, backward walking task and stand-still condition.

2.3 Protocol Design

Three healthy male participants were included in this pilot study, with age between 30 and 50 years old. All subjects cooperated voluntarily and provided written informed consent to the procedures of the study, which was approved by the

Ethics Committee of Politecnico di Milano. The TD-NIRS device has been mounted on a backpack custom support and was comfortably worn by all subjects, thanks to its compactness and relatively lightweight (< 2.5 kg). The optical probe has been placed over the right lower limb motor cortex. Subjects have been asked to perform the following protocol: 20 s standing still (baseline), 20 s walking on a straight line (task) and 20 s standing still (recovery), repeated 5 times in a row for a total time of 5 minutes. At the end of the five repetitions, an extra recovery block of 20 s has been implemented. Three kinds of task have been considered: forward walking, backward walking and stand still (control condition). For both forward and backward walking tasks, the subjects have been asked to keep a constant stride time during the task and equal walking speed between the exercises.

2.4 Data Analysis

The data acquisition frequency was set to 1 Hz (500 ms of integration time for each wavelength). Baseline optical values have been estimated using an homogeneous model to approximate the measured media, while for the task duration, raw acquisitions have been processed through the convolved photon path lengths method [11]. It was therefore possible to distinguish between hemodynamic information relative to the upper layer (extracerebral variation) and deeper layer (brain cortex area) of the head. Exploiting an already existing adaptive hemodynamic response model [12] which utilizes a linear combination of two opposite signs gamma functions, it was possible to describe the brain cortex hemodynamic behaviors, both for oxygenated and deoxygenated hemoglobin.

3. RESULTS

Three different healthy male volunteers have been measured. In Figure 2 it is possible to observe the results of the functional brain activation of one of these subjects. Different columns represent the three tasks performed by the subject, while the two rows represent the upper and lower layer of the head, respectively.

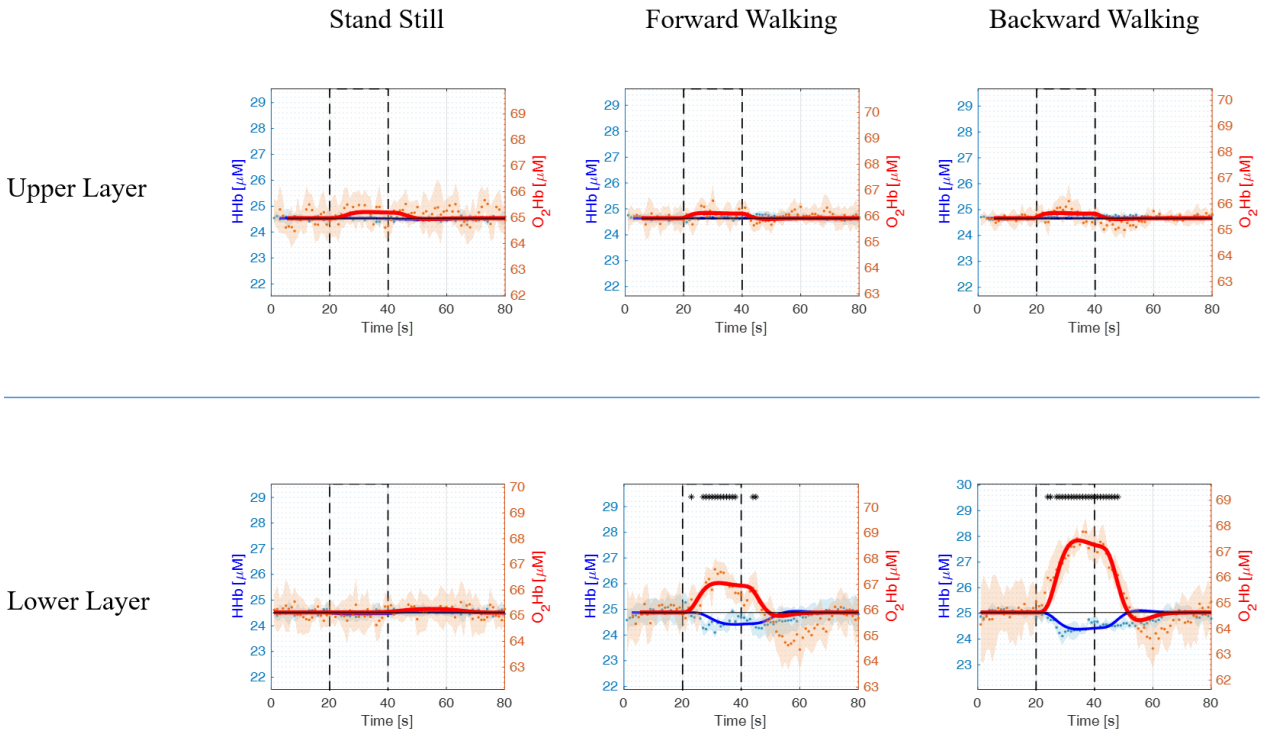

Figure 2 Results from one subject of the functional brain hemodynamic measurement on the lower limb motor cortex area, during the walking protocol. Data are divided into upper layer contribution (extracerebral) and lower layer contribution (brain cortex). Five repetitions of the protocol have been averaged. Oxygenated and deoxygenated hemoglobin temporal behaviors are shown (red and blue dots/lines respectively). Shaded curves represent the standard deviation over the 5 repetitions. Solid lines show the adaptive hemodynamic response function fit over raw data. Shaded-gray areas highlight the task period in which the subject is moving. Asterisks on the upper part of the subplots highlight the time points in which the hemodynamic variations are significant ($p < 0.05$)

Asterisks on the upper part of the subplots highlight the time points in which the hemodynamic variations, with respect to baseline, are significant ($p < 0.05$). As expected, the activation of the lower limb motor cortex area results in a task-related increase of oxygenated hemoglobin and a concomitant decrease of deoxygenated hemoglobin in the deeper brain regions. From Figure 2 we can also notice that the activation intensities are greater in the case of the backward walking task, compared with forward walking. For each task, the variations have been fitted with an adaptive hemodynamic response function model [12] (solid lines). Even if the subjects have been left free to move, measurements do not show any significant motion artifact related to head natural motions or instrument's movements during the gaiting tasks.

4. DISCUSSIONS

The conventional method used so far to investigate cortical activations in locomotion is by exploiting fMRI scanners, during motor imagery tasks. Many fMRI studies have confirmed that similar brain areas are activated as if the movement was actually being performed ([14],[15],[16],[17]). It is clear, though, that the brain cortex areas and hemodynamic behaviors involved during a motor task that is actually performed in ecological condition by the subject may not be identically reproduced in case of imaginary motor tasks. In the study by Godde *et al.* [9], in which the imaginary motor task can be considered similar to the task we proposed in our work, a wider area of supplementary motor area and primary motor cortex (SMA/M1) activates during imaginary backward gaiting together with a more intense blood oxygen level-dependent (BOLD) signal. Our study, in which the single-channel probe was placed close to the barycenter of the activation seen in [9], confirms that even in real gaiting task the activation is grater in case of backward gaiting. In the same work an earlier decrease of the BOLD fMRI signal was also seen in case of forward walking, resulting in a shorter activation response to the imaginary task. Our results are also in accordance with other CW-NIRS studies even if they have been performed in less natural and ecological environment [18].

From a physiological point of view, the stronger activation and the wider area involved in the backward walking task, with respect to the forward walking task, could be due to a major involvement of the SMA. A major motor awareness is needed to control and plan movements during backward walking, proprioception could also play a substantial role in the increase of the brain motor-cortex involvement.

Diagnostic oriented studies could, eventually, focus on the activation variability that has been found in older adults, compared to younger ones, for what concerns complex gaiting task. Elderly individuals show less selective recruitment of brain areas than younger ones [19]. Stronger activations of sparse brain areas can suggest a lower capability to appropriately address-specific neuronal mechanisms [20]. In such population and neurological patients, it can be hypothesized that the difference in the activation between the two studied tasks is lowered due to recruitment of different zones limiting the implication of the M1 area. A quantitative test such as the one proposed in this study can be a possible diagnostic tool to evaluate the entity and evolution of those neurological pathologies that directly affect stable gaiting.

5. CONCLUSIONS

We showed the possibility to obtain hemodynamic measurements on cerebral tissues with the portable TD-NIRS system we developed, operating as a backpack on freely-moving subjects. The system proved to work without any degradation in performances in ecological measurement conditions, being also battery-operated and wirelessly controlled, with very low sensibility to motion artifacts.

6. ACKNOWLEDGMENTS

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7. DISCLOSURES

M.L., M.B., A.D.M., F.Z., A.P, A.T., A.T. and D.C. are co—founders of pioNIRS s.r.l., Italy. Other authors declare that there are no conflicts of interest related to this article.

REFERENCES

[1] J. Verghese, A. LeValley, C. B. Hall, M. J. Katz, A. F. Ambrose, and R. B. Lipton, "Epidemiology of gait disorders in community-residing older adults," *J. Am. Geriatr. Soc.*, vol. 54, no. 2, pp. 255–261, 2006.

[2] S. Heinrich, K. Rapp, U. Rissmann, C. Becker, and H. H. König, "Cost of falls in old age: A systematic review," *Osteoporos. Int.*, vol. 21, no. 6, pp. 891–902, 2010.

[3] H. Wabnitz *et al.*, "Performance assessment of time-domain optical brain imagers, part 1: basic instrumental performance protocol.," *J. Biomed. Opt.*, 19(8), 086010 (2014).

[4] A. Pifferi *et al.*, "Performance assessment of photon migration instruments: the MEDPHOT protocol," *Appl. Opt.*, 2005.

[5] H. Wabnitz *et al.*, "Performance assessment of time-domain optical brain imagers, part 1: basic instrumental performance protocol," *J. Biomed. Opt.*, vol. 19, no. 8, p. 086010, 2014.

[6] E. Martinenghi, L. Di Sieno, D. Contini, M. Sanzaro, A. Pifferi, and A. Dalla Mora, "Time-resolved single-photon detection module based on silicon photomultiplier: A novel building block for time-correlated measurement systems," *Rev. Sci. Instrum.*, vol. 8, no. 7, 073101, (2016).

[7] M. Buttafava *et al.*, "A Compact Two-Wavelength Time-Domain NIRS System Based on SiPM and Pulsed Diode Lasers," *IEEE Photonics J.*, vol. 9, no. 1, pp. 1–14, 2017.

[8] M. Lacerenza *et al.*, "Wearable and wireless time-domainnear-infrared spectroscopy system for brainand muscle hemodynamic monitoring," *Biomed. Opt. Express*, vol. 11, no. 10, pp. 5934–5949, 2020.

[9] B. Godde and C. Voelcker-Rehage, "More automation and less cognitive control of imagined walking movements in high- versus low-fit older adults," *Front. Aging Neurosci.*, vol. 2, no. 139, pp. 1–13, 2010.

[10] A. D. Mora *et al.*, "Towards next-generation time-domain diffuse optics for extreme depth penetration and sensitivity," *Biomed. Opt. Express*, vol. 6, no. 5, p. 1749, 2015.

[11] L. Zucchelli, D. Contini, R. Re, A. Torricelli, and L. Spinelli, "Method for the discrimination of superficial and deep absorption variations by time domain fNIRS," *Biomed. Opt. Express*, vol. 4, no. 12, pp. 2893–2910, 2013.

[12] M. Uga, I. Dan, T. Sano, H. Dan, and E. Watanabe, "Optimizing the general linear model for functional near-infrared spectroscopy: an adaptive hemodynamic response function approach," *Neurophotonics*, vol. 1, no. 1, p. 015004, 2014.

[13] D. Contini, A. Torricelli, A. Pifferi, L. Spinelli, F. Paglia, and R. Cubeddu, "Multi-channel time-resolved system for functional near infrared spectroscopy," *Opt. Express*, Vol. 14, Issue 12, pp. 5418-5432 (2006).

[14] K. M. Stephan *et al.*, "Functional anatomy of the mental representation of upper extremity movements in healthy subjects," *J. Neurophysiol.*, vol. 73, no. 1, pp. 373–386, 1995.

[15] M. Lotze *et al.*, "Activation of cortical and cerebellar motor areas during executed and imagined hand movements: An fMRI study," *J. Cogn. Neurosci.*, vol. 11, no. 5, pp. 491–501, 1999.

[16] C. Sahyoun, A. Floyer-Lea, H. Johansen-Berg, and P. M. Matthews, "Towards an understanding of gait control: Brain activation during the anticipation, preparation and execution of foot movements," *Neuroimage*, vol. 21, no. 2, pp. 568–575, 2004.

[17] C. la Fougère *et al.*, "Real versus imagined locomotion: A [18F]-FDG PET-fMRI comparison," *Neuroimage*, vol. 50, no. 4, pp. 1589–1598, 2010.

[18] B. R. Groff, P. Antonellis, K. K. Schmid, B. A. Knarr, and N. Stergiou, "Stride-time variability is related to sensorimotor cortical activation during forward and backward walking," *Neurosci. Lett.*, vol. 692, no. September 2018, pp. 150–158, 2019.

[19] R. D. Seidler *et al.*, “Motor control and aging: Links to age-related brain structural, functional, and biochemical effects,” *Neurosci. Biobehav. Rev.*, vol. 34, no. 5, pp. 721–733, 2010.
[20] J. M. Logan, A. L. Sanders, A. Z. Snyder, J. C. Morris, and R. L. Buckner, “Under-recruitment and nonselective recruitment: Dissociable neural mechanisms associated with aging,” *Neuron*, vol. 33, no. 5, pp. 827–840, 2002.