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Motor Cortex Hemodynamic Response Function in Freely Moving Subjects Recorded via Time Domain fNIRS

Michele Lacerenza*[a], Mauro Buttafava[b], Lorenzo Spinelli[c], Alberto Tosi[b], Alberto Dalla Mora[a], Franco Zappa[b], Antonio Pifferi[a,c], Bruno Cozzi[d], Alessandro Torricelli[a,c], Davide Contini[a]

[a] *Dipartimento di Fisica, Politecnico di Milano, Italy*
[b] *Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Italy*
[c] *Consiglio Nazionale delle Ricerche, Istituto di Fotonica e Nanotecnologie, Italy*
[d] *Dipartimento di Biomedicina Comparata e Alimentazione, Università degli Studi di Padova, Italy.*
**michele.lacerenza@polimi.it*

Abstract: We report on motor cortex hemodynamic responses to different motor tasks on humans in ecological environment. The portable, time-domain near-infrared spectroscopy (TD-NIRS) device we present enables cerebral hemodynamic measurements on freely moving subjects.

1. Introduction

TD-NIRS proved to be a reliable technique to monitor functional cerebral hemodynamic activations during various types of tasks performed by human subjects [1]. Compared to other NIRS techniques, TD-NIRS can disentangle absorption and scattering coefficients, has the possibility of retrieving absolute concentration of chromophores (such as absolute oxygenated and deoxygenated hemoglobin values) and is characterized by high immunity to motion artifacts. In fact, the retrieval of optical parameters relies on the modifications of the laser pulses temporal shape and not, for example, on the light intensity [2]. These features make TD-NIRS a valuable candidate for cerebral hemodynamic recordings on freely moving human subjects. Gold standard functional hemodynamic brain monitoring techniques, such as functional magnetic resonance (fMRI), cannot measure human subjects in ecological conditions, due to current technical limitations. We developed a portable TD-NIRS device to access human cerebral hemodynamics during freely moving exercises.

2. Materials and methods

2.1. Compact TD-NIRS device

The device used in this study is a dual-wavelength (680 nm, 830 nm) single-channel portable TD-NIRS system developed at Politecnico di Milano [3], with custom-made optics and electronics. Laser light is transferred to (and recollected from) the brain tissue by means of graded-index optical fibers hosted in a 3D printed probe [4]. Backscattered light from the tissue is detected through a custom silicon photomultiplier (SiPM) module and photons arrival times are processed through a time-correlated single-photon counting application-specific integrated circuit. The system is battery-operated and remotely controlled via Wi-Fi. Being lightweight (2.5 kg) and compact, it can be accommodated within a backpack-like support.

2.2. Measurement Protocol

Subjects have been enrolled to perform three different motor tasks. For each different task, the subjects performed 5 repetitions of the following procedure: 20 s baseline, 20 s task, 40 s recovery (Fig. 1). The baseline periods have been used to acquire the hemodynamic values at rest; the recovery period is doubled with respect to the others to appreciate the full temporal dynamic of the brain activation. The three different tasks are: finger tapping protocol, contralateral to the target cerebral area (subject seated on a chair); forward walking on a straight line; and backward walking on a straight line. Probe placement was set to C3 position (following the EEG 20/20 system) in case of finger-tapping task and C1 (lower limb motor cortex area) for forward and backward walking tasks. The acquisition rate of the physiological parameter was set to 1 Hz with 500 ms integration time for each wavelength (the two laser pulses were time-multiplexed); the stride time was kept constant in both gaiting tasks.

2.3. Data Analysis

Hemodynamic variations, in terms of oxygenated and deoxygenated hemoglobin concentrations, have been retrieved through the time-dependent mean partial pathlength (TMPP) method [5]. Baseline absorption and reduced scattering values have been retrieved through the homogeneous model.

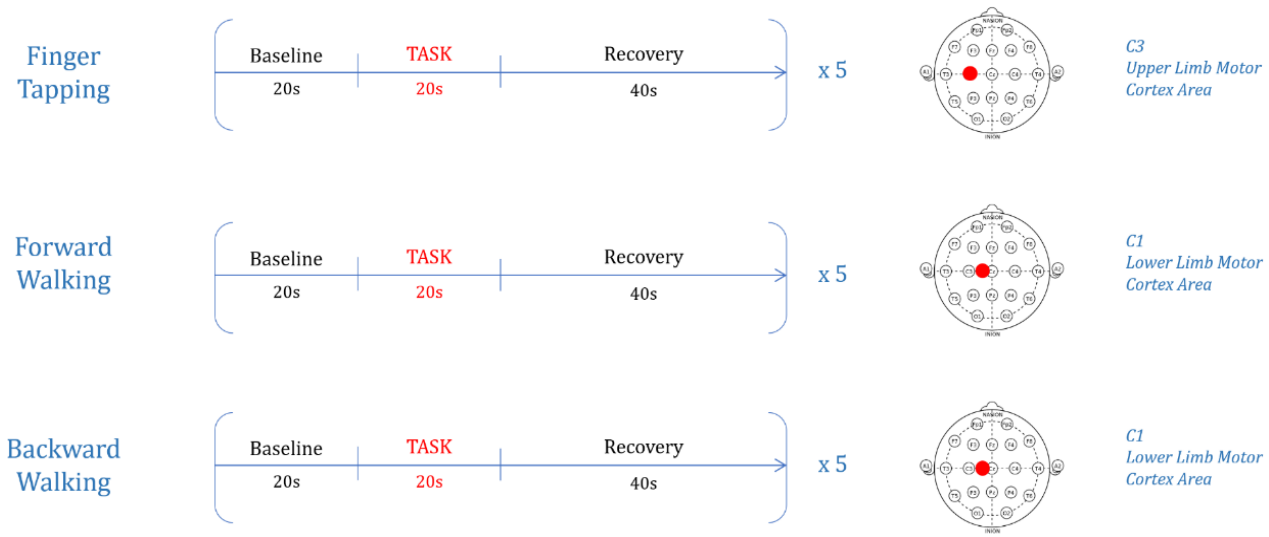

Fig. 1: Each line refers to a different motor task, whose protocol is described between blue brackets. Each block has been repeated five times (x5). Sketches on the right show the probe position (red mark) over a simplified map of the 10/20 EEG system.

Thanks to the TMPP method it was possible to retrieve deep brain layer information deprived of the possible contribution of hemodynamic variations of the shallower layers. The five repetitions for each motor task have been averaged and fitted with an adaptive hemodynamic response function (HRF) model, to retrieve the expected hemodynamic brain activation. Such model was previously used by Uga et al. [6] and it exploits a linear combination of two gamma functions of opposites signs and performs the convolution of the theoretical response function with a boxcar time function as wide as the task duration. The matching of fitting vs. raw data has been evaluated with the Pearson correlation coefficient (R): $R < 0.3$ translates in weak correlation, $0.3 < R < 0.7$ in moderate correlation and $R > 0.7$ in high correlation. The procedure has been inspired by the standard protocols used in fMRI for functional brain activation analysis retrieved from the blood oxygenation level-dependent signal [7].

3. Results

Fig. 2 shows the results of the motor cortex hemodynamic activation of one of the subjects. The average over five repetitions is reported for each task: results are in agreement with previous literature [8]. Red and blue dots represent the concentration of oxygenated and deoxygenated hemoglobin. Shaded areas show the standard deviation over the five repetitions, oxygenated hemoglobin in orange and deoxygenated hemoglobin in cyan, respectively. Solid thick lines are the result of the adaptive HRF fitting procedure. All subjects showed similar results, no filtering has been applied on the acquired raw data, and no significant motion artifacts have been noticed.

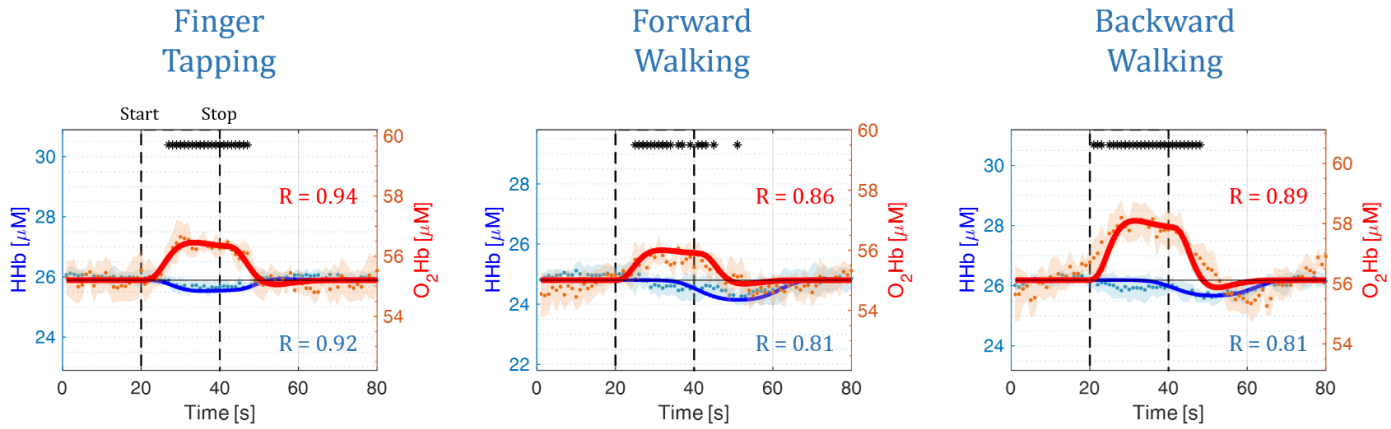

Fig. 2: Results from the cerebral hemodynamics recording of one subject during the three motor tasks. Five repetitions have been averaged and the adaptive HRF (solid lines) model has been superimposed to the acquired data points (full dots). The task period is enclosed between dashed black lines and significant hemodynamic variations ($p<0.05$) are marked with black asterisks. The Pearson Correlation coefficient (R) is shown on the graphs for both oxygenated hemoglobin (red text) and deoxygenated hemoglobin (blue text).

Substantial cerebral hemodynamic variations have been retrieved in every motor task and, as expected, an increase of the oxygenated hemoglobin concentration has been noticed with a concomitant decrease of the deoxygenated hemoglobin during the task period. It is possible to notice that the three hemodynamic variations show different behaviors for the three different motor tasks. The Pearson correlation coefficient (R) is shown on the graphs for both oxygenated hemoglobin (red text) and deoxygenated hemoglobin (blue text). For both hemoglobin species and both tasks, the fitting results highly match the datapoints.

4. Discussions and Conclusions

Cerebral HRFs of human subjects was successfully retrieved in three different motor tasks. Hemodynamic variations have been proved to be significant and not substantially affected by motion artifacts. The averaged cerebral activations showed differences in the hemodynamic behaviors, both in terms of amplitude and delay of the activation peak from the beginning of the task. The amplitude of the oxygenated hemoglobin variation during the motor task is similar in the case of finger tapping and forward walking task, while the activation seems to have doubled intensity in the backward walking task compared to forward walking. The deoxygenated hemoglobin decrease during the walking tasks seems to have a longer duration and to be delayed in time with respect to the finger-tapping activation. The adaptive hemodynamic response function model was exploited to fit the average cerebral hemodynamic behaviors and retrieve output parameters that could summarize such activations.

From a preliminary fitting quality analysis, the adaptive HRF model showed acceptable results in the case of upper limb motor cortex activations, during a finger-tapping task, while it showed suboptimal results in the case of lower limb motor cortex activations (walking exercises). Following previous studies [6] only two free variables have been set in the fitting procedure: amplitude of the first peak and its delay from the start of the task. The amplitude of the second gamma function (the negative one, responsible for the oxy-hemoglobin undershoot) and its delay have been fixed, to the same values reported in [6].

In the near future, a deeper study on the optimal adaptive hemodynamic response function fitting model for motor task brain activations will be performed, different canonical HRF will be tested and a higher number of variables will be included in the fitting procedure.

Due to the restricted population under study, it is preliminary to draw significant conclusions on the effectiveness of the adaptive HRF fitting model used. Nevertheless, this work sets the basis for developing a more sophisticated model to fit functional TD-NIRS cerebral activations in humans.

5. 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.

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