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Towards a BCI for Sensorimotor Training: Initial Results from Simultaneous fNIRS and Biosignal Recordings

Raphael Zimmermann, Laura Marchal-Crespo, Olivier Lambercy, Marie-Christine Fluet, Robert Riener*, Martin Wolf* and Roger Gassert*

Abstract— **This paper presents the concept and initial results of a novel approach for robot assisted sensorimotor training in stroke rehabilitation. It is based on a brain-body-robot interface (B^2RI), combining both neural and physiological recordings, that detects the intention to perform a motor task. By directly including the injured brain into the therapy, we ultimately aim at providing a new method for severely impaired patients to engage in active movement therapy. In the present study, seven healthy subjects performed an isometric finger pinching task while functional near-infrared spectroscopy (fNIRS) signals from motor cortical areas and biosignals were recorded simultaneously. Results showed an insignificant increase in the blood pressure during the preparation period prior to motor execution. During the execution period, significant changes in oxy- and deoxyhemoglobin were found in the primary motor cortex, accompanied by an increase in blood pressure, respiration rate and galvanic skin response (GSR). Cortical measurements of premotor areas and heart rate revealed significant changes at the subject level with large inter-subject variability. The results presented here will serve as priors for the design of further studies to test the efficacy of the concept with stroke patients, and the found effects will provide a basis for the development of a classifier for a future B^2RI.**

I. INTRODUCTION

Conventional stroke rehabilitation strategies for patients with remaining motor function are based on active movement therapy [1], [2]. However, about one third of stroke survivors suffer from severe impairment of motor function and cannot engage in conventional physical training. These patients can only undergo passive therapy which has been shown to be less efficient than therapy in which the patient participates actively [3]. Therefore, current rehabilitation strategies must be revisited in order to provide active movement therapy to a wider group of stroke patients. The ideal approach would include the actual source of the impairment, i.e. the brain, into the therapy in combination with assistive devices. Brain-computer interfaces (BCIs) could be used to control rehabilitation robots to move the impaired limb when an intention to move is detected from cortical activity. This approach could provide a way to assist the injured brain in shaping new sensorimotor loops.

*Shared last co-authorship

R. Zimmermann, O. Lambercy, M.-C. Fluet and R. Gassert are with the Rehabilitation Engineering Laboratory, ETH Zurich, Switzerland {raphaezi, olambercy, mfluet, gassertr}@ethz.ch

L. Marchal-Crespo and R. Riener are with the Sensory-Motor Systems Laboratory, ETH Zurich, Switzerland and with the Medical Faculty, Balgrist University Hospital, University of Zurich, Switzerland {laura.marchal, riener}@mavt.ethz.ch

R. Zimmermann and M. Wolf are with the Biomedical Optics Research Laboratory, University Hospital Zurich, Switzerland {raphael.zimmermann, martin.wolf}@usz.ch

The most prominent non-invasive systems to monitor cortical activation are electroencephalography (EEG), magnetoencephalography (MEG), functional magnetic resonance imaging (fMRI) and functional near-infrared spectroscopy. EEG has been successfully employed in BCIs [4]. However, the training process that allows the user to mentally control the EEG response is difficult and time-consuming, and the setup time can be very long [5]. MEG has been employed recently in a BCI-based hand orthosis for stroke patients [6]. Its high sensitivity to electromagnetic disturbances and immobility however prevents MEG to be used in day-to-day therapy approaches. Functional MRI provides high spatial resolution and whole-brain coverage. However, it is inappropriate in a standard therapeutic environment due to its safety and compatibility constraints, high sensitivity to movement of the patient and the high cost. On the contrary, fNIRS is well suited for BCI purposes. It is easy to use, inexpensive and does not require a priori training of the subject. Furthermore, it can be miniaturized and operated wirelessly [7]. We therefore focused on the development of a fNIRS-based BCI that will be employed in robot assisted stroke rehabilitation.

fNIRS is an emerging method to non-invasively measure activation of the adult human brain and has been successfully applied to neuroimaging since the 1990s [8]. Light of two (or more) distinct wavelengths in the near-infrared spectrum is emitted on the surface of the scalp and penetrates the tissue. The blood concentration changes in oxyhemoglobin (oxy-Hb) and deoxyhemoglobin (deoxy-Hb) in the probed tissue are calculated from the spectral attenuation measured a few centimeters away from the source. Due to neurovascular coupling, changes in oxy- and deoxy-Hb concentrations represent an indirect measure of neuronal activity [9]. Cortical activation leads to a higher energy demand and an increase in regional cerebral blood flow (rCBF) which causes the concentration of oxy-Hb to rise and the concentration of deoxy-Hb to decrease (washout-effect).

The fNIRS signal does not only reflect the level of neuronal activation, but also physiological signals, such as changes in heart rate (HR), mean blood pressure (MBP), nasal air flow and respiration frequency. Studies with brain-computer interfaces based on EEG have shown that the inclusion of systemic signals in the signal analysis can improve the decoding performance [10]. Systemic signals such as heart rate, blood pressure and respiration also have an influence on fNIRS recordings from cortical regions [11], [12] and need to be taken into account in fNIRS-based

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BCIs. Furthermore, the physiological signals might contain additional information that can be used to estimate a subject's emotional state or mental workload. Combined, these signals can create the basis for a brain-body-robot interface.

In this paper, we present an initial study on seven healthy subjects to investigate the response of cortical signals from premotor and primary motor cortex measured with fNIRS and physiological recordings during an isometric finger pinching task. The task was selected based on its importance in activities of daily living. A preparation cue was introduced to investigate the response of the systemic signals during this period [13] as well as its influence on the cortical signals during motor execution [14]. The isometric pinching task was used to study activity in motor areas and the accompanying changes in the physiological signals.

II. METHODS

A. Procedure

Seven healthy subjects (22 to 29 years old, 26.0 $\pm$ 2.2 y, 1 female) participated in the study. Two fNIRS probes were attached to the participant's head with self-adhesive bandages, one over the premotor cortex (PMC) and one over the primary motor cortex (M1) on the contralateral side (left hemisphere). These areas were selected for the placement of fNIRS probes due to their involvement in preparation and execution of finger movement. The localization was done based on the international 10-20-system for EEG-probes (M1 location at C3; PMC location at FC5) [15].

The blood-pressure monitor (CNAP monitor 500, CNSystems) was attached to the left arm and hand. The ECG-electrodes (g.tec) were placed on the chest and the GSR electrodes (g.GSRsensor, g.tec) were attached to the left index and middle fingers. The respiration flow sensor (SleepSense) was placed in close proximity to the nares. The physiological measurement devices were connected to a biosignal amplifier (g.USBamp, g.tec) which sent the data via USB to the host PC. The force sensor used to perform the pinching task (CentoNewton 100N, LPM-EPFL) was attached to the tips of the right index finger and thumb with Velcro® straps. The voltage from the force sensor was recorded via a DAQ card (NI USB-6008, National Instruments Inc.) which was connected via USB to the host PC.

The protocol was implemented in Simulink® (The MathWorks Inc.) running on the host PC. The fNIRS data acquisition was controlled by a separate laptop. In order to synchronize the two systems, digital signals were sent from the host to the fNIRS computer through the NI USB-6008 to indicate the current state of the protocol. Visual feedback was provided through video goggles (Zetronix z920HR-VGA). A schematic representation of the hardware setup is shown in Fig. 1. During the measurements, subjects were in a supine position.

B. Tasks

Subjects performed an isometric finger pinching task with the right index finger and thumb in opposition. Three different instructions (Fig. 2) were visually provided:

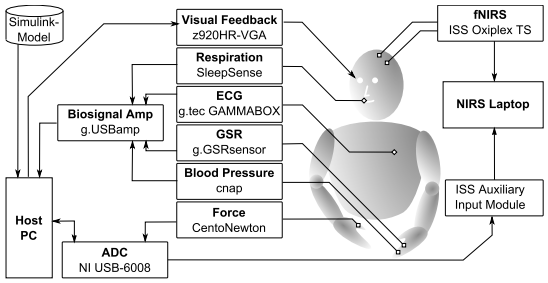

Fig. 1. Schematic representation of the experimental setup. The physiological signals are acquired on a host PC while the fNIRS signals are acquired on a laptop. The two computers are synchronized over a digital channel.

- During the *rest period*, the word "rest" was displayed on the right side of the screen (Fig. 2A) and subjects were requested to relax.
- During the *preparation period*, the text "get ready" was displayed on the right (Fig. 2B). Subjects were requested to prepare for the squeezing task and try to minimize the reaction time when the squeezing instruction was given, but without contracting their muscles.
- During the *execution period*, the word "squeeze" was displayed on the right side of the screen. Subjects were asked to match a reference force, generated with a truncated Fourier series with frequencies 0.5 Hz, 1 Hz and 1.1 Hz, by pinching isometrically. The reference force was shown as a green horizontal bar on the lower left and the generated force as a light gray bar on the upper left (Fig. 2C).

Four different temporal arrangements of instructions were employed (Fig. 3), each making one condition (C1-C4).

- C1 & C2: a preparation period (10 or 5 seconds duration, respectively) was followed by an execution period (20 seconds duration).
- C3: a preparation period (10 seconds duration) was presented, but was directly followed by a resting period without motor execution.
- C4: an execution period was cued (20 seconds duration) without a prior preparation period.

The order of the conditions was randomized and a resting period of randomized duration (15-24 s) was introduced between each condition. This was done in order to reduce potential adaptation effects and to avoid synchronization between oscillating systemic effects (mostly Mayer-waves) and the protocol.

Each condition was presented 10 times. The trials were separated into two sessions of about 20 minutes each with a break of about 10 minutes in between. Each session began with a baseline measurement of 180 seconds and ended with a baseline of 120 seconds. The pre-stimulus baseline served primarily to stabilize the subjects' physiological and mental state. The total duration of the recording was about 50 minutes.

Fig. 2. To inform the subject about the current condition, visual feedback and instructions were provided over video-goggles. A: instruction to rest. B: instruction to prepare. C: Instruction to perform the motor task, i.e. pinching the right index finger and thumb to match the applied force (shown in the upper gray bar) with the reference force (shown in the lower green bar).

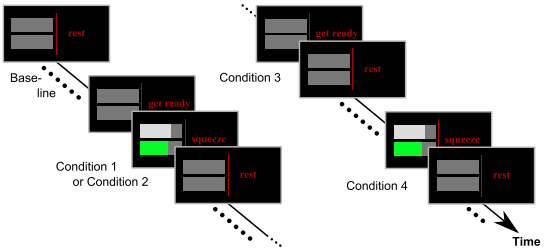

Fig. 3. Schematic representation of the experimental protocol (one single session). The time-line is split for illustration purposes and shows the protocol and the combinations in which the three instructions (Fig. 2) are presented. The pre-trial baseline data acquisition is also indicated.

C. fNIRS signal processing and data analysis

The tissue oximeter (Oxiplex TS, ISS Inc., Champaign IL) was used to measure cortical signals at a sampling rate of 50 Hz. The OxiTS software (ISS Inc.) was used to monitor the fNIRS signals during recordings. Each probe (Adult Flexible Sensor, ISS Inc.) has four light paths (interoptode distances: 2, 2.5, 3.5 and 4 cm). The intensity of the detected light for each path and two wavelengths (692 and 834 nm) was stored on the fNIRS laptop and processed offline using Matlab® (The MathWorks, Inc.).

The data were filtered using a second-order Chebychev type-II low-pass filter (40 dB attenuation at 0.5 Hz) in order to remove high-frequency oscillations such as pulsation [12]. The truncated direct cosine transformation (DCT) cut at approximately 0.02 Hz was subtracted in order to remove low frequency fluctuations and signal drift. This cutoff frequency corresponded approximately to the longest possible time period between the onsets of two consecutive conditions. The data's DC-component was left unaffected by the filtering due to the logarithmization used in the modified Beer-Lambert law (MBLL). The processed signals were then separated into fragments containing one trial that is preceded by 5 seconds of rest and followed by 10 seconds of rest. The MBLL was used to calculate differential changes in oxy- and deoxy-Hb [16] with respect to the fragment's mean values. Differential path length factors (DPF) of 6.51 and 5.86 were used for the 692 nm and 834 nm wavelength, respectively [17]. The data were visually inspected for motion artifacts and the affected fragments were excluded. The remaining fragments of the same condition is called a block.

In order to investigate changes in the different fNIRS signals between the rest and the preparation periods, the mean of the first 3 seconds of the rest period was compared to the mean from 3 seconds during the preparation period shifted by 3 seconds from the beginning of the preparation period. In order to investigate changes in the different fNIRS signals between the rest and the squeeze periods, the mean of the first 3 seconds of the rest period was compared to the mean from a 3 seconds window during the squeeze period. This window was shifted by 6 to 8 seconds from the onset of the squeeze period. The delay for which the difference of the means was the largest was identified for each subject independently. This allowed to account for the inter-individual variability in the hemodynamic response. From the four different light paths of each fNIRS probe, the one that showed the largest signal difference was chosen. Paired t-tests were used to investigate the presence of significant changes between rest and preparation periods as well as between rest and squeeze periods for individual subjects and at the group level. The significance level was set to 5%.

D. Biosignal processing and data analysis

All biosignals were acquired through a g.USBamp amplifier and processed offline in Simulink® and Matlab®. The blood pressure signal was detrended by removing the linear fit from the signal of each session and low-pass filtered with a cutoff frequency of 0.1 Hz to study only the low and very low frequency spectra of the signal. From the electrocardiogram, the QRS complex was filtered with a bandpass filter with a frequency band of 0.01-40 Hz. The heart rate was calculated using an adaptive threshold on the squared derivative signal from the QRS complex [18]. The breathing signal, measured by the nasal thermistor flow sensor, was filtered with a bandpass filter with a frequency band of 0.1-2 Hz. The breathing frequency was calculated using an adaptive threshold similar to the one used with QRS. The GSR was filtered by a low-pass filter with a cutoff frequency of 30 Hz and linearly detrended to remove the drift over time using the start of each trial as a breakpoint. The GSR data was further normalized.

The processed biosignals were fragmented into blocks according to the four different conditions as described for the fNIRS signals in Section II-C. In order to investigate the changes in the different biosignals between the rest and the preparation phases, the mean during the last 3 seconds in the rest period was compared to the mean from 3 seconds during the preparation period shifted by 3 seconds from the beginning of the preparation period. In order to investigate the changes in the different biosignals between the rest and the squeeze periods, the mean of the last 5 seconds of the rest period was compared to the mean value from 5 seconds during the squeeze period. Because different biosignals have a different latency response (i.e the GSR is faster than other systemic changes), different times after the onset of the squeeze period were used for each signal. A latency time of 3 seconds post-stimulus was used for the GSR and 5 seconds for all the other biosignals. Paired t-tests were used to evaluate the presence of a change in each biosignal between the rest and preparation periods as well as between the rest and squeeze periods for individual subjects and at the group level. The significance level was set to 5%. Due to technical problems, the biosignals of subject 1 and the GSR

of subject 7 were not recorded.

III. RESULTS

Typical fNIRS signals (oxy- and deoxy-Hb) measured in M1 and PMC during the execution period are shown in Fig. 4. A higher oxy-Hb signal could be observed in M1 and PMC during the execution period compared to the following rest period. The deoxy-Hb signal in M1 was lower during the execution period compared to the following rest period while no real trend could be seen in PMC. The results of the statistical comparison of the signals during the rest and execution periods for individual subjects are shown in Figs. 5 and 6 for fNIRS signals and biosignals respectively. Table I summarizes the results of the group analysis. Statistical comparison of the fNIRS signals during rest and preparation periods did not reveal any significant changes at the group level, neither in M1 nor in PMC. Comparison of the rest and execution periods showed a significant increase in oxy-Hb (mean $\pm$ std: 0.184 $\pm$ 0.134 μM, p = 0.0108) and a significant decrease in deoxy-Hb (mean $\pm$ std: -0.064 $\pm$ 0.062 μM, p = 0.0329) in M1 in the group analysis. In PMC, statistical comparison of rest and execution periods did not reveal significant changes at the group level. No homogeneous results could be found accross subjects.

The skin conductance showed no significant change between the rest and the preparation period. However, the GSR significantly increased for all subjects between the rest and the execution period (mean $\pm$ std: 0.369 $\pm$ 0.126, p = 0.0028). Further analysis revealed that this GSR increase was significantly higher in condition 4 compared to condition 1 (p = 0.0011). For blood pressure, a non-significant increase was observed between rest and preparation periods. Between the rest and the execution period, 5 of 6 subjects showed an increase of which 4 were significant. Furthermore, the blood pressure change between rest and execution periods was significantly higher in condition 4 compared to condition 2 (p = 0.0077). For the respiration rate, 5 of 6 subjects showed an increase of which 4 were significant between the rest and the execution periods. For the heart rate, 3 of 6 subjects showed significant changes between the rest and the execution periods, but no significant effect was observed at the group level. Overall, fNIRS signals from M1, blood pressure, respiration rate and GSR showed clear trends while fNIRS signals from PMC and heart rate showed large inter-subject-variability.

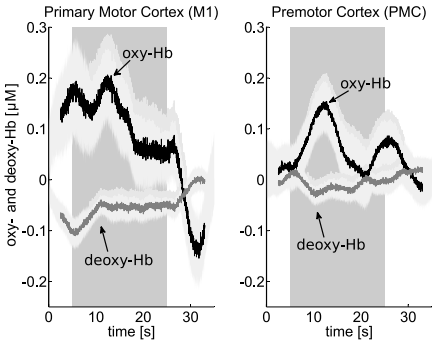

Fig. 4. Oxy- and deoxy-Hb signals obtained from subject 1 in M1, path 1 (left) and PMC, path 3 (right). The signal corresponds to the average results (mean $\pm$ SEM) for all pinching trials with and without preparation phase ($N = 30$). For this reason the signal is shown only for the execution period (indicated by the gray shading of 20 seconds duration).

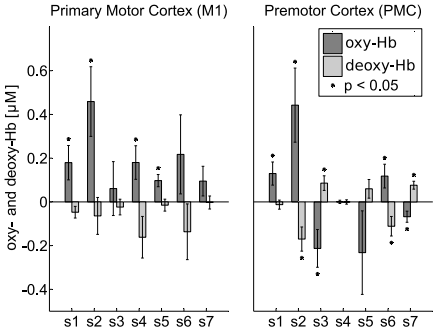

Fig. 5. Variation in oxy- (dark gray) and deoxy-Hb (light gray) signals between the execution and rest periods in M1 (left) and in PMC (right) for each subject. Number of trials for each subject: $N_1 = 30$, $N_2 = 25$, $N_3 = 26$, $N_4 = 30$, $N_5 = 26$, $N_6 = 30$, $N_7 = 30$. Errorbars indicate the standard error of the mean. * indicates significance at the 5%-level (paired, two-sided t-test).

IV. DISCUSSION

This paper presented a new concept for a brain-body-robot interface with the long-term aim to use the combination of multi-sensory data (i.e. cortical signals, HR, blood pressure, GSR, and respiration) to detect the intention to move as well as fatigue and motivation of the subject, and control a robotic assistive device to move the impaired limb for sensorimotor rehabilitation. As a first step towards the design of such a hybrid B^2RI, we investigated the activation of cortical motor areas measured with fNIRS and the changes in physiological signals during an isometric finger pinching task with healthy volunteers. In the current protocol, we included a preparation period in order to investigate the changes in the biosignals and the cortical data when the subject is in an aroused state. Subjects were asked to be more concentrated in order to minimize the reaction time for the following squeezing period. Our results did not show significant changes in the measured signals during the preparation period. The blood pressure showed a tendency to increase, but this increase was not significant. Our instruction might elicit a mental state which is not well defined and may differ among subjects. Thus, there was no clear effect at the group level between rest and preparation. Furthermore, changes in blood pressure and GSR were bigger during the execution period when it was not preceded by a preparation period. During the execution period, a consistent increase in oxy-Hb and a consistent decrease in deoxy-Hb was found for all subjects in M1. In PMC, a large inter-subject variability was observed for both oxy- and deoxy-Hb. However, for most subjects these changes in oxy- and/or deoxy-Hb were significant and might therefore be useful for a B^2RI on a single subject level. During the training phase of a decoder, e.g. in a Markov model classifier, the typical responses of a subject can be measured and later used to classify the signals more

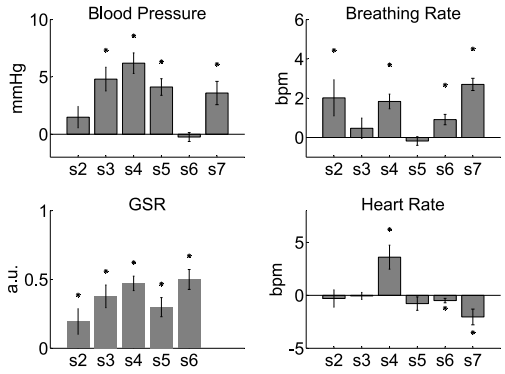

Fig. 6. Variation in biosignals between the execution and rest periods for each subject. All results are based on 30 repetitions. Errorbars indicate the standard error of the mean. * indicates significance at the 5%-level (paired, two-sided t-test). bpm: beats per minute. a.u.: arbitrary units.

TABLE I

GROUP-LEVEL ANALYSIS OF THE CHANGES BETWEEN THE EXECUTION AND REST PERIODS

signal	units	mean	std	p	N
O_2Hb, M1	μM	0.184	0.134	0.0108	7
HHb, M1	μM	-0.064	0.062	0.0329	7
O_2Hb, PMC	μM	0.025	0.233	0.7828	7
HHb, PMC	μM	-0.010	0.098	0.7893	7
BP_{low}	mmHg	3.327	2.335	0.0175	6
resp	bpm	1.293	1.076	0.0321	6
GSR	a.u.	0.369	0.126	0.0028	5
HR	bpm	-0.009	1.904	0.9914	6

std: standard deviation. p: p-value (paired two-sided t-test). N: number of subjects analyzed. bpm: beats per minute. O_2Hb: oxy-hemoglobin. HHb: deoxy-hemoglobin. M1: primary motor cortex. PMC: premotor cortex. BP_{low}: low-pass-filtered blood pressure. resp: respiration frequency. GSR: galvanic skin response. HR: heart rate.

accurately. A similar argumentation applies for the change in heart rate which also showed large inter-subject variability. The blood pressure, breathing rate and galvanic skin response showed a consistent increase during isometric pinching, with the galvanic skin response showing the clearest signal change during pinching, identifying it as an important signal for our B^2RI.

V. CONCLUSION & OUTLOOK

The next step towards our B^2RI system is the automatic classification of the recorded signals. The results presented here indicate that the fNIRS signals from M1 and the GSR are important priors for this purpose. The observed inter-subject variability will be further investigated on further healthy subjects and should be taken into account in the design of a future B^2RI. The simultaneous recording of cortical and physiological signals will allow to investigate the synergetic properties of these two measurement modalities and the use of multiple signals has the potential to increase the robustness of the system.

VI. ACKNOWLEDGEMENTS

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