
This file was downloaded from: http://eprints.qut.edu.au/64613/

© Copyright 2013 IRSTEA – France

Notice: Changes introduced as a result of publishing processes such as copy-editing and formatting may not be reflected in this document. For a definitive version of this work, please refer to the published source:
Comparison between electrically-evoked and voluntary wrist movements on sensorimotor and prefrontal cortical activation: A multi-channel time domain fNIRS study

M. Muthalib*ab, R. Re*c, L. Zucchelli*c, S. Perreyd, D. Continic, M. Caffinid, L. Spinellie, G. Kerrb, A. Torricellic

*authors contributed equally to the work

aMovement To Health (M2H) Laboratory, EuroMov, Montpellier-1 University, Montpellier, France
bMovement Neuroscience Program, IHBI, Brisbane, Australia
cDipartimento di Fisica, Politecnico di Milano, Milan, Italy
dDipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Milan, Italy
eIstituto di Fotonica e Nanotecnologie, CNR, Milan, Italy

Corresponding author:
Makii Muthalib, PhD
Movement to Health (M2H) Laboratory, EuroMov, Montpellier-1 University, 700 Avenue du Pic Saint Loup, 34090, Montpellier, France
E-mail: makii.muthalib@univ-montp1.fr/makii.muthalib@gmail.com
Phone: +33-411759066
Fax: +33-411759050
Abstract
A time domain 32-channel fNIRS instrument was employed to map bilateral sensorimotor (SMC) and prefrontal (PFC) cortical activities during voluntary (VOL) and neuromuscular electrical stimulation (NMES)-evoked wrist extension movements in nine healthy volunteers. The NMES-evoked wrist extension paradigm significantly increased activation of the contralateral SMC, which was comparable to VOL. However, a greater bilateral SMC and PFC activation was found during the higher NMES current intensities, which could be due in part to a nociceptive response to NMES.

Introduction
Neuromuscular electrical stimulation (NMES) has been consistently demonstrated to improve skeletal muscle function in neurological populations with movement disorders, such as post-stroke and incomplete spinal cord injury (Vanderthommen and Duchateau, 2007). Recent research has documented that rapid supraspinal central nervous system reorganisation/neuroplastic mechanisms are also implicated during NMES (Chipchase et al., 2011). Functional neuroimaging studies have shown NMES to activate a network of sub-cortical and cortical brain regions, including the sensorimotor (SMC) and prefrontal (PFC) cortex (Blickenstorfer et al., 2009; Han et al., 2003; Muthalib et al., 2012). A relationship between increase in SMC activation with increasing NMES current intensity up to motor threshold has been previously reported using fMRI (Smith et al., 2003). However, since clinical neurorehabilitation programmes commonly utilize NMES current intensities above the motor threshold and up to the maximum tolerated current intensity (MTI), limited research has determined the cortical correlates of increasing NMES current intensity at or above MTI (Muthalib et al., 2012). In our previous study (Muthalib et al., 2012) we assessed contralateral PFC activation using a 1-channel functional near infrared spectroscopy (fNIRS) during NMES of
the elbow flexors by increasing the current intensity from motor threshold to over MTI, and showed a linear relationship between NMES current intensity and the level of PFC activation. However, the relationship between NMES current intensity and activation of the motor cortical network, including the SMC and PFC, has not been clarified. Moreover, it is of scientific and clinical relevance to know how NMES affects the central nervous system, especially in comparison to voluntary (VOL) muscle activation. Therefore, the aim of this study was to utilise multi-channel time domain fNIRS to compare SMC and PFC activation between VOL and NMES-evoked wrist extension movements.

Material and Methods

Subjects

Nine healthy volunteers (39±13y, 8 male and 1 female) participated in this study. All the subjects had no known health problems or any upper extremity muscle or joint injuries. Subject enrolment in the study and related data handling were in accordance to the guidelines established by the local Institutional Review Board.

Equipment

NMES

NMES was carried out with the portable system CEFAR Physio 5 (DJO France SAS, France). The right wrist extensor muscles were stimulated (biphasic symmetrical rectangular pulse shapes at 30 Hz and 200 µs pulse width) with a pair of 5 cm x 5 cm self-adhesive electrodes. Four NMES current intensities were used based on individual’s MTI: 10%MTI (4±1 mA), 50%MTI (18±4 mA), MTI (36±7 mA) and over-MTI (66±14 mA).

fNIRS
A 32-channel time domain fNIRS medical device developed at the Department of Physics Politecnico di Milano (Contini et al., 2006) was used. A total of 16 detection bundles and 10 light sources were positioned centered over the bilateral SMC and PFC regions. Sequential illumination of pairs of light sources in the left and right hemisphere every 0.2s allowed for the acquisition of 32 channels with an overall acquisition time of 1s. Oxygenated hemoglobin (O$_2$Hb) and deoxygenated hemoglobin (HHb) changes in the SMC and PFC regions were estimated by a method based on the use of late time-gate to enhance the contribution of the signal from deeper cortical regions and to reduce the contribution from superficial layers (i.e. scalp, skull) (Molteni et al., 2012).

**Protocol**

Subjects initially performed VOL wrist extension movements followed by the four NMES conditions (10%MTI, 50%MTI, MTI and over-MTI) in a blocked design. Each condition consisted of 10 blocks of 20s baseline followed by 20s task (1s contraction/stimulation, 1s rest) and 20s rest. A 2 min rest period followed each of the conditions. Subjective pain rating was monitored using a 12-point pain rating scale (PRS).

**Analysis**

General linear model (GLM) analysis using statistical parametric mapping (SPM) was applied to the fNIRS data of a single subject first and then to the whole group by using the NIRS-SPM software (Ye et al., 2009). Regressors and design matrix were constructed so that cortical activation was indicated by an increase in the O$_2$Hb concentration and by a decrease for HHb concentration. GLM analysis of the whole group was performed using NIRS-SPM separately for VOL and each NMES condition compared to baseline (rest), and also by contrasting each NMES condition with the VOL condition. The T statistics on contrasted regressors were calculated for every channel, and interpolated T values were then computed over the whole probe extension.
Results

The VOL condition produced overt wrist extension movements with no subjective indications of pain or discomfort. The 50%MTI, MTI and over-MTI NMES conditions produced similar wrist extension movements as those produced during VOL, however, the stimulations were mild/moderately painful for the 50%MTI condition (PRS: 2±1) and were high/extremely painful for both MTI and over-MTI conditions (PRS: 5±1 and 7±1, respectively). The 10%MTI NMES condition did not produce wrist movements nor produced pain/discomfort, and were generally perceived as tingling sensations.

Figure 1. NIRS-SPM cortical activation maps (N=9, p<0.05, uncorrected) for O$_2$Hb (top row) and HHb (bottom row) compared to the baseline period during the voluntary (VOL) and NMES-evoked wrist extension movements (left to right column: VOL, 50%MTI, MTI, over100%MTI). The 10%MTI showed no significant effect compared to baseline.

Figure 1 shows the group cortical O$_2$Hb and HHb SPM activation maps during the VOL and NMES conditions compared to baseline (rest). In each panel the spatial distribution of the T values is plotted. The VOL condition significantly increased cortical activation (i.e., increase in O$_2$Hb and concomitant decrease in HHb) of the contralateral SMC region, while the ipsilateral SMC and
bilateral PFC regions showed no significant changes. The NMES-evoked wrist extension paradigms (50%MTI, MTI and over-MTI) also showed significant increases in contralateral SMC activation, and the $O_2$Hb maps indicated smaller significant increases in ipsilateral SMC and bilateral PFC activation. No SMC or PFC regions were significantly activated above baseline levels during the 10%MTI condition.

Figure 2. NIRS-SPM cortical activation maps (N=9, p<0.05, uncorrected) for $O_2$Hb (top row) and HHb (bottom row) during the NMES-evoked wrist movements. Contrasts versus the voluntary (VOL) condition (left to right column: 50%MTI vs. VOL, MTI vs. VOL, and over-MTI vs. VOL). The 10%MTI showed no significant effects.

Figure 2 shows the cortical $O_2$Hb and HHb SPM activation maps obtained contrasting each NMES condition with the VOL condition. Both the $O_2$Hb and HHb contrast maps indicated that 50%MTI, MTI and over-MTI activated a significantly greater region of the contralateral SMC compared to VOL. The $O_2$Hb contrast maps also indicated that, compared to VOL, the over-MTI condition activated the ipsilateral SMC and bilateral PFC, while smaller ipsilateral SMC and PFC activations were found in the 50%MTI and MTI conditions. The HHb contrast maps primarily showed a
greater region of the contralateral SMC activation with the increase in NMES current intensity, but no ipsilateral activation (see Figure 2).

Discussion

To the best of our knowledge this is the first time that multi-channel fNIRS has been employed to compare SMC and PFC activation between VOL and NMES-evoked movements. As expected, VOL resulted in activity of the contralateral SMC that is well known to be associated with motor tasks (Leff et al., 2011; Muthalib et al., in press). Although NMES principle lies in applying repeated electrical currents to the peripheral motoneuronal axons that elicit either isometric or concentric muscle contractions, NMES also activates peripheral sensory neuronal axons that send proprioceptive and nociceptive signals from the stimulated muscle to the central nervous system leading to changes in cortical plasticity and activation (Chipchase et al., 2011; Hortobagyi and Maffiuletti, 2011). In the present study, NMES above the motor threshold (50%MTI, MTI and over-MTI) increased fNIRS-derived contralateral SMC activation which is in agreement with previous fMRI findings (Blickenstorfer et al., 2009; Han et al., 2003; Smith et al., 2003). A novel finding of the present study was that the contralateral SMC activation region found during NMES-evoked movements (50%MTI, MTI, and over-MTI) was comparable to VOL, although with a greater region of activation surrounding the contralateral SMC. The clinical benefits of NMES have been proposed to be via a sensorimotor integration mechanism whereby increased proprioceptive signals from evoked movements activate the SMC thereby increasing cortical excitability, and facilitating greater voluntary activation of the relevant neuronal network (Hortobagyi and Maffiuletti, 2011; Ridding and Rothwell, 1999). The present study findings suggest that electrically-evoked wrist extension movements (50%MTI, MTI, and over-MTI) activated brain regions related to sensorimotor integration. It is possible that the higher bilateral SMC and PFC activation found during NMES at higher current intensities are due to both
increased nociceptive processing and sensorimotor integration in these cortical regions (Muthalib et al., 2012).

Conclusion
This study has shown that NMES-evoked movements activate a relatively similar contralateral SMC region compared to VOL, and increasing the NMES current intensities activate a larger bilateral SMC and PFC region compared to VOL. This study provides a better understanding of how therapeutic NMES interacts with the central nervous system, which may allow for improved neurorehabilitation therapy monitoring.

Acknowledgments
The authors would like to thank Prof. Marco Ferrari and Dr. Valentina Quaresima for their contribution to the project.

References


