Mobile Brain/Body Imaging (MoBI): High-density electrical mapping of inhibitory processes during walking.

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Abstract— **The present study investigated the feasibility of acquiring high-density event-related brain potential (ERP) recordings during treadmill walking in human subjects. The work builds upon recent studies testing the applicability of real-world tasks while obtaining electroencephalographic (EEG) recordings. Participants performed a response inhibition GO/NOGO task – designed to evoke a P3 component for correct response inhibitions and an error-related negativity (ERN) for incorrect commission errors – while speed of walking was experimentally manipulated. Robust P3 and ERN components were obtained under all experimental conditions - while participants were stationary, walking at moderate speed (2.4 km/hour), or walking rapidly (5km/hour). Signal-to-noise ratios were remarkably similar across conditions, pointing to the feasibility of high-fidelity ERP recordings under relatively vigorous activity regimens. There is considerable research and clinical motivation to obtain high quality neurophysiological measures under more naturalistic environmental settings such as these. Strong links between cognitive load and gait abnormalities are seen in a number of clinical populations and these MOBI technologies provide highly promising methods for gaining insights into the underlying pathophysiology.**

I. Introduction

Experimental designs capable of testing neuro-cognitive processes while participants actively explore an environment will allow us to answer questions of high ecological validity and with significant clinical implications. For example, it has been suggested that initiating a postural adjustment during walking might be compromised if one is engaged in a secondary task, and that this increases risk of falls in older adults [1]. Evidence of compromised cortical functioning during walking while talking might help identify individuals at heightened risk for falls, a leading cause of death and disability in adults over the age of 65 [2]. However, before we can address this issue in clinical populations, we must first establish the feasibility of such designs in the general population, and identify brain functions suitable for measuring modulation of task-related cognitive processes during walking. Recently, advances have been made in conducting electroencephalogram (EEG) recordings during passive or active movement [3-10]. These studies have opened new possibilities for acquiring electrophysiological data in ecologically valid situations.

Here, we deployed a variation of the *Mobile Brain/Body Imaging* (MoBI) approach developed by Scott Makeig's group [6-10], which continually measures a participant's high-density electrical brain and muscle signals while tracking three-dimensional body movements. These studies showed that relatively noise-free scalp EEG can be acquired while participants walk on a treadmill.

Here we complement previous findings, testing for differential effects of walking upon brain functions supporting two levels of processes, task-specific and task-general processes. To this end, we deployed event-related brain potentials (ERPs) to measure cortical activity while participants performed a GO/NOGO task. For task-specific processes, we assessed the N2/P3 components [11] related to successful response inhibition, and for task-general processes, we assessed the error-related negativity (ERN) [12] associated with monitoring and eventually adjusting task performance during and following errors. Our exploratory hypothesis was that walking would particularly interfere with task-general processes, namely the ability to monitor task performance.

II. Methods

A. Participants

Five neurologically healthy participants (4 male, 1 female) with normal or corrected-to-normal vision participated in the experiment. The age range was 21 – 32 years (mean 24.6 ±4.8). Subjects gave their informed consent before taking part in the experiment, which was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

B. Motion Capture

Kinematic data were collected at 100 Hz using a redundant 6 camera OptiTrak R2 system and Arena v1.7.2 data acquisition software (NaturalPoint). For this study, a single 4 marker rigid body was placed at the shoulder to measure trunk angle variability. In future studies, bilateral full body kinematics will be measured (i.e. C7, shoulder, lumbar, hip, knee, ankle, heel, and fifth metatarsal).

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C. Stimuli and Task

We used 168 pictures from the International Affective Picture System (IAPS; [13]), a set of normative photographs that includes content across a wide range of semantic categories. Affective neutral valenced images were presented centrally for 600ms with a random inter-stimulus-interval ranging from 200 to 400ms. On average, images subtended 28° horizontally by 28° vertically. Participants performed a GO/NOGO task, responding quickly and accurately to every presentation by clicking the left mouse button, while withholding responses to the second instance of any stimulus repeated twice in a row. The probability of GO and NOGO trials was 0.85 and 0.15, respectively.

Participants were asked to stand, walk slowly (2.4 km/hr), or quickly (5 km/hr) on a treadmill (LifeFitness TR-9000) approximately 1.5m from a black wall, onto which stimulus images were projected (InFocus XS1 DLP, 1400 x 1050 pxl) Figure 1. Participants completed 12 blocks (approximately 4 minutes apiece), consisting of 4 blocks for each of the 3 conditions. Conditions were presented in a pseudorandom order. Subjects rested between conditions to prevent fatigue. Total testing time was between 60 and 90 minutes.

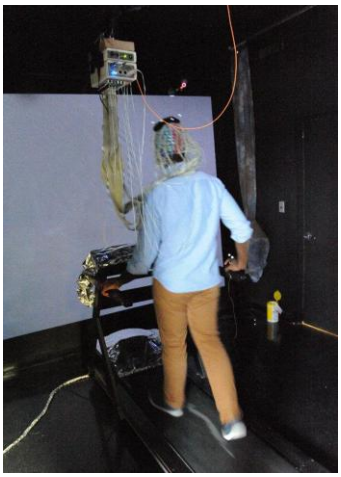

Figure 1: Illustration of an participant walking on the treadmill wearing an EEG cap while performing the GO/NOGO-task.

C. Data Analysis

Brain activity was recorded using a 72-channel EEG system (BioSemi). The data were recorded at 512 Hz and bandpass filtered from 1 to 40Hz (24 dB/octave). The data were analyzed offline using the Matlab programming language (Mathworks). We applied an automatic artifact rejection criterion of ±75 μV across all electrodes in the array. Trials with more than six artifact channels were rejected. For the stimulus-locked ERP we extracted epochs of 900ms with 100ms pre-stimulus baseline from the continuous data for the GO and NOGO trials. For the response-locked ERP we extracted epochs of 800ms with 600ms pre-response baseline from the continuous data.

Regions of interest were identified from the literature, the electrode cluster surrounding the fronto-central midline area for the GO and NOGO and the response locked ERP.

To confirm that there was minimal contamination of the broadband evoked response from muscles and eye movements which are commonly shown in frequencies of 8Hz or higher, we computed the Fast Fourier Transform on the epoched GO trials for each participant for all three conditions. We computed the correlation coefficient matrix for each participant and for the group average.

III. Results

A. Behavioral Results

Figure 2 shows reaction time (RT on go-trials) and accuracy (commission errors on nogo-trials) for performing the GO/NOGO task while participants were sitting, walking slow and walking fast. Average RT increases by about 10ms when participant perform the task while walking compared to sitting. In contrast, errors rate decrease while walking. The one-way ANOVA for RT and commission errors revealed no difference between conditions (RT: $f_{2,14}$= 0.17, p =0.84; error: $f_{2,14}$= 0.72, p =.51).

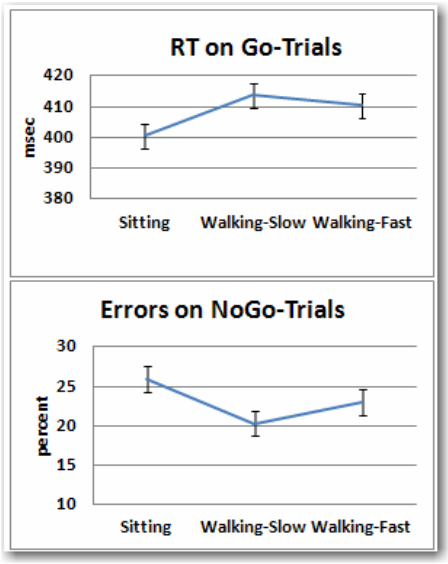

Figure 2. RT on GO-trial and commission errors on NOGO-trials while performing the GO/NOGO task sitting, walking slow, and walking fast.

B. Motion Capture Results

Figure 3 shows exemplar kinematic data from 1 participant. The data show a rhythmic bob in the medio-lateral and anterior-posterior direction, which did not contaminate the ERP data. Further analysis and a more comprehensive marker set will allow us to characterize postural adjustments corresponding to task load.

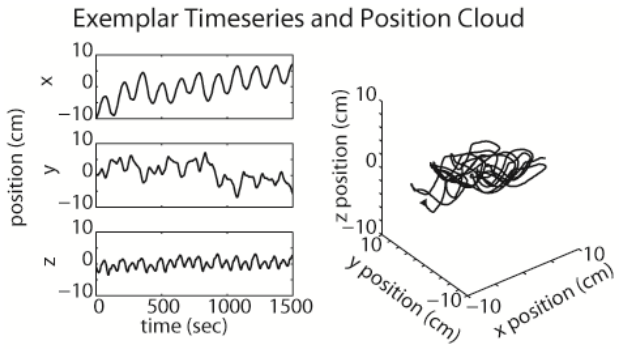

Figure 3. Left: Exemplar x (mediolateral), y (vertical), and z (anteriorposterior) position timeseries (cm) for walking at 2.4 km/hr. Right: Exemplar 3-dimension position cloud for the same timeseries of data.

C. Electrophysiological Results

Figure 4 shows an average across five electrodes over fronto-central region for the stimulus-locked N2/P3 component on correct trials (right panels) and for the response-locked ERN component on incorrect trials (left panels) for performing the GO/NOGO task while participants were sitting, walking slow and walking fast. A robust NOGO-N2 was evident across all three conditions: (t_{14}= 7.45, p <.001). An NOGO-N2 increase was only evident in the sitting condition. However, statistical testing revealed no differences between GO/NOGO-trials and conditions. In contrast, a robust NOGO-P3 increase was evident across all three conditions.

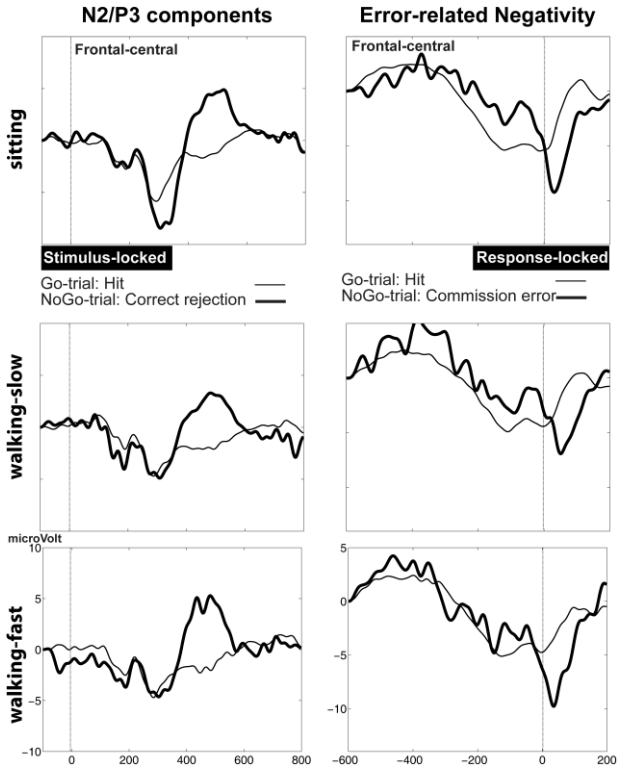

Figure 4. Top: The N2/P3 component (right) and ERN component (left) over fronto-central scalp region for GO-trials and NOGO-trials for performing the task while sitting, walking slow and walking fast.

The one-way ANOVA for the NOGO-P3 revealed no differences between conditions ($f_{2,14}$= 0.39, p =.68). We therefore combined the sitting, walking slow and walking fast conditions and ran a t-test on the difference wave between GO- and NOGO-trials to test the significance of the NOGO-P3 increase (t_{14} = 7.1, p <.0001). Furthermore, a robust ERN was evident across all three conditions: (t_{14}= 5.22, p <.001). The one-way ANOVA for the ERN revealed no differences between conditions ($f_{2,14}$= 1.22, p =.54). Signal-to-noise ratio (SNR) was measured in a window of 80ms around the largest absolute peak of the GO trials versus 80ms in the pre-stimulus baseline period as a means of comparing sensitivity of our measures across movement conditions. The means (SD) of SNRs across the subjects were: Sitting =21.46dB (8.8); Walking =18.46dB (10.2); Walking Fast =20.55dB (8.5). All three SNRs are extremely robust, pointing to the high sensitivity of our measures.

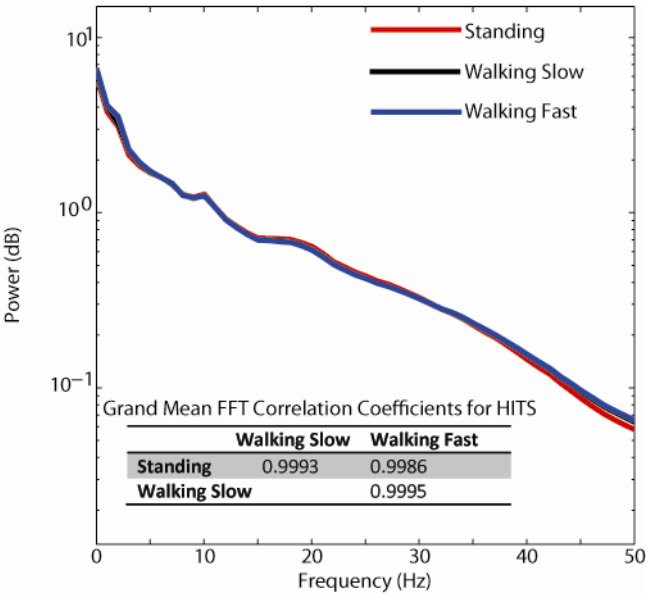

Figure 5 Group mean spectra of each motion condition.

Figure 5 shows the group average spectra for each of the motion conditions. The table embedded in the figure shows strong correlation coefficients (greater than 0.99) across the movement conditions. Thus suggesting that there was little to no contamination of artifacts from muscle or eye movements due to walking.

IV. Discussion

We set out to build upon recent studies [6-8, 10] using an ecologically valid paradigm to acquire task-related EEG electrophysiological data during walking. Our data confirmed that robust ERP components can be obtained with similar morphology while participants perform the GO/NOGO task sitting, walking slow and walking fast. We extended previous findings by assessing the influence of

walking upon brain function supporting task-specific and task-general processes. Increased NOGO-P3 related to successful response inhibition was found, with similar morphology for sitting, walking slow and walking fast. Also, the ERN related to failed response inhibition was similar across sitting, walking slow and walking fast. Our preliminary data suggest that walking caused no modulation upon brain processes supporting the performance and the monitoring of the GO/NOGO task.

V. Conclusion

Here we have shown that cognitive ERP experiments can be conducted while the participants walked. These results replicate the work of Makeig lab and extend the applications of this recently developed method.

References

[1] M. Woollacott and A. Shumway-Cook, "Attention and the control of posture and gait: a review of an emerging area of research," *Gait & Posture*, vol. 16, pp. 1-14, Aug 2002.

[2] J. A. Stevens, "Falls among older adults - risk factors and prevention strategies," *Journal of Safety Research*, vol. 36, pp. 409-411, 2005.

[3] H. Nolan, J. S. Butler, R. Whelan, J. J. Foxe, H. H. Bulthoff, and R. B. Reilly, "Neural correlates of oddball detection in self-motion heading: A high-density event-related potential study of vestibular integration," *Exp Brain Res*, Mar 21 2012.

[4] H. Nolan, J. S. Butler, R. Whelan, J. J. Foxe, H. H. Bulthoff, and R. B. Reilly, "Motion P3 demonstrates neural nature of motion ERPs," *Conf Proc IEEE Eng Med Biol Soc*, vol. 2011, pp. 3884-7, Aug 2011.

[5] H. Nolan, R. Whelan, R. B. Reilly, H. H. Bulthoff, and J. S. Butler, "Acquisition of human EEG data during linear self-motion on a Stewart platform," in *Neural Engineering, 2009. NER '09. 4th International IEEE/EMBS Conference on*, 2009, pp. 585-588.

[6] S. Makeig, K. Gramann, T. P. Jung, T. J. Sejnowski, and H. Poizner, "Linking brain, mind and behavior," *Int J Psychophysiol*, vol. 73, pp. 95-100, Aug 2009.

[7] J. T. Gwin, K. Gramann, S. Makeig, and D. P. Ferris, "Removal of movement artifact from high-density EEG recorded during walking and running," *J Neurophysiol*, vol. 103, pp. 3526-34, Jun 2010.

[8] J. T. Gwin, K. Gramann, S. Makeig, and D. P. Ferris, "Electrocortical activity is coupled to gait cycle phase during treadmill walking," *Neuroimage*, vol. 54, pp. 1289-96, Jan 15 2011.

[9] K. Gramann, J. T. Gwin, D. P. Ferris, K. Oie, T. P. Jung, C. T. Lin, L. D. Liao, and S. Makeig, "Cognition in action: imaging brain/body dynamics in mobile humans," *Rev Neurosci*, vol. 22, pp. 593-608, 2011.

[10] K. Gramann, J. T. Gwin, N. Bigdely-Shamlo, D. P. Ferris, and S. Makeig, "Visual evoked responses during standing and walking," *Front Hum Neurosci*, vol. 4, p. 202, 2010.

[11] M. Eimer, "Effects of Attention and Stimulus Probability on ERPs in a Go/Nogo Task," *Biological Psychology*, vol. 35, pp. 123-138, Apr 1993.

[12] M. Falkenstein, J. Hoormann, and J. Hohnsbein, "ERP components in Go/Nogo tasks and their relation to inhibition," *Acta Psychol (Amst)*, vol. 101, pp. 267-91, Apr 1999.

[13] P. J. Lang, M. M. Bradley, and B. N. Cuthbert, "International affective picture system (IAPS): Affective ratings of pictures and instruction manual. ," *Technical Report A-8. University of Florida, Gainesville, FL.* , 2008.