

Clenching-Related Motion Artifacts in Functional Near-Infrared Spectroscopy in the Auditory Cortex

Fan Zhang, *IEEE Student Member*, Adaira Reid, Alissa Schroeder, Mallory Cutter, Kaitlyn Kim, Lei Ding, *IEEE Member*, Han Yuan, *IEEE Member*

Abstract— Functional near-infrared spectroscopy (fNIRS), a non-invasive optical neuroimaging technique, has demonstrated its great potential in monitoring cerebral activity as an alternative to functional magnetic resonance imaging (fMRI) in research and clinical usage. fNIRS has seen increasing applications in studying the auditory cortex in healthy subjects and cochlear implant users. However, fNIRS is susceptible to motion artifacts, especially those related to jaw movement, which can affect fNIRS signals in speech and auditory tasks. This study aimed to investigate the motion artifacts related to jaw movements including clenching, speaking, swallowing, and sniffing in a group of human subjects, and test whether our previously established denoising algorithm namely PCA-GLM can reduce the motion artifacts. Our results have shown that the jaw movements introduced artifacts that resemble task-evoked activations and that the PCA-GLM method effectively reduced the motion artifacts due to the clenching movements. The preliminary results of the present study underline the importance of the removal of the jaw-movement-related artifacts in fNIRS signals and suggest the efficacy of our PCA-GLM method in reducing the motion artifacts.

Clinical Relevance— This work studies the motion artifacts due to jaw movements that frequently occur in speech perception and production tasks and validates the efficacy of an established denoising algorithm, which benefits fNIRS studies on auditory and language functions.

I. INTRODUCTION

Functional near-infrared spectroscopy (fNIRS) is a promising, noninvasive neuroimaging technology that measures hemodynamic responses in the brain using near-infrared light [1]. fNIRS is more economical, portable, and accessible compared to other neuroimaging methods such as functional magnetic resonance imaging (fMRI). Furthermore, it provides a solution for patients with medical electronic implants (e.g., cochlear implants) that are often incompatible with fMRI. Therefore, fNIRS has been increasingly employed to monitor brain activity in research and clinical environments [2].

One of the booming applications of fNIRS is in studying speech perception and production [3, 4]. There are several features of fNIRS that make it a unique tool for studying auditory and language functions. fNIRS is quiet compared

with fMRI in which the scanner generates loud operating noise. The silent environment could avoid interferences with auditory stimulation and other psychological effects such as stress and fear, which have been shown to induce activations in the auditory cortex [5]. Unlike fMRI and even electroencephalography (EEG) or magnetoencephalography (MEG), fNIRS has no interference with cochlear implants or hearing aids, as it uses near-infrared light to measure the blood-oxygenation-level-dependent (BOLD) signals. Furthermore, as the optodes of light emitters and detectors are mounted on a cap attached to the head, fNIRS is considered relatively less sensitive to head movements [6] and does not require participants to be constrained in a head-fixed position, which makes it suitable for cohorts with limited tolerance and compliance, including infants, children and the elderly.

However, there are still several confounding factors in fNIRS signals, including interferences from superficial layers of the head, systemic physiological noises and motion artifacts [7]. Although less vulnerable to head movements, fNIRS can still suffer from jaw movements such as speech speaking and voluntary jaw clenching, which can cause contractions of the temporalis muscle. The jaw movements could result in blood flow changes in the temporal muscle as well as relative movements between the optodes and the scalp, leading to artifacts in the fNIRS signals. While many previous studies have investigated the impact and correction of head movements [6, 8-10], the effect and especially handling of jaw movements in fNIRS signals remain largely unclear [11, 12].

In this study, we aimed to investigate the presentation of jaw-movements-related artifacts in fNIRS and test whether our previously established denoising pipeline namely PCA-GLM [7] can reduce the jaw movement artifacts. We conducted two experiments to realize this aim. Experiment 1 investigated four types of jaw movements, including clenching, speaking, swallowing and sniffing, in order to characterize the spatial and temporal profiles in the fNIRS oxyhemoglobin (HbO) and deoxyhemoglobin (HbR) responses. Based on the results of experiment 1, we further focused on the jaw clenching in experiment 2, to investigate the motion artifacts and test whether the PCA-GLM can reduce the clenching-related artifacts.

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Fan Zhang, Adaira Reid, Alissa Schroeder and Mallory Cutter are with the Stephenson School of Biomedical Engineering, University of Oklahoma, Norman, OK, USA.

Kaitlyn Kim was with the Stephenson School of Biomedical Engineering, University of Oklahoma, Norman, OK, USA. She is now with the

Department of Biomedical Engineering, University of California, Irvine CA, USA.

Lei Ding and Han Yuan are with the Stephenson School of Biomedical Engineering and the Institute for Biomedical Engineering, Science and Technology, University of Oklahoma, Norman, OK, USA.

Correspondence to Han Yuan: 3100 Monitor Ave, Norman, OK 73072, USA. E-mail: hanyuan@ou.edu, Phone: +1 405-325-4665.

II. MATERIALS AND METHODS

A. Experimental Setup and Data Acquisition

Informed consent was obtained from each subject before the beginning of each experiment. All study protocols were approved by the Institutional Review Boards at The University of Oklahoma Health Sciences Center.

Experiment 1: Three healthy participants (two females) aged 18-25 years participated in Experiment 1. Participants were instructed to perform four different tasks including (1) speaking the word 'red' silently, (2) clenching the jaw, (3) swallowing and (4) sniffing the nose in a comfortable sitting position. Each task was repeated in two sessions. Every session contains six blocks, which include a jaw-movement period of 20 s and a resting period of 30 s. During the jaw-movement period, the participants were instructed to perform the movement at 1 Hz signalled by a visual cue displayed on a computer screen at a distance of six feet from the subject. These tasks were designed to introduce jaw movements without explicitly activating the auditory cortex.

Experiment 2: Ten healthy participants (seven females) aged 18-37 years participated in Experiment 2. Data from one subject (female) were discarded due to bad optical coupling. Participants were instructed to perform two sessions of a jaw-clenching task in a comfortable sitting position. A jaw-clenching session consisted of seven blocks, each of which included a clenching period of 20 s and a resting period of 30 s. The participants were instructed to perform the jaw clenching at 0.15 Hz (i.e., with an interval of 6.67 s) guided by a visual cue.

A NIRScout system (NIRX, New York, United States) was used to collect fNIRS data at a sampling rate of 3.91 Hz. 16 light sources (760 nm and 850 nm) and 20 light detectors were arranged over the left and right auditory cortices to form an array with 54 long-separation (LS) (about 30-mm) channels. In addition, 16 short-separation (SS) (8-mm) detectors were placed around each source and constructed 16 SS channels. Physiological measurements including triaxial acceleration, respiration, and cardiac pulsation were also simultaneously collected by a 64-channel actiChamp system (Brain Vision, North Carolina, United States), in a similar setting in [7].

B. fNIRS Data Preprocessing

fNIRS data were preprocessed using Homer2 [13] and proprietary codes in MATLAB® (The Mathworks, Natick, MA) reported in our previous work [7]. Specifically, the data were preprocessed following these steps: 1) converting the raw data into optical densities (ODs); 2) calculating the power spectral densities of each channel using the Welch's method with a time window of 60 s and 50% overlapping and rejecting bad channels which showed no peak at heartbeat frequency range (0.8-1.6 Hz); 3) bandpass filtering ODs with 0.008-0.2 Hz; 4) converting the filtered ODs to relative changes of oxy-hemoglobin (HbO) and deoxy-hemoglobin (HbR) using the modified Beer-Lambert law (MBLL) [1]. The differential pathlength factors of 7.25 and 6.38 were used for 760 nm and 850 nm, respectively [14]. The molar extinction coefficients were 645.5 cm⁻¹/M and 1097.0 cm⁻¹/M for HbO and 1669.0 cm⁻¹/M and 781.0 cm⁻¹/M for HbR at 760 nm and 850 nm, respectively [15].

C. Correcting fNIRS Signals with Linear Regression

A general linear model (GLM) was configured per session for denoising processing. A third-order polynomial drift and a clenching regressor which accounts for the clenching effects were included in the design matrix. The clenching regressor was derived by convolving the stimuli structure with a canonical two-gamma hemodynamic response function (HRF) model [16]. This GLM model was referred to as No Correction.

In addition, a more advanced model namely PCA-GLM [7] was configured per session for data from Experiment 2. A superficial systemic component (PC-SS) was identified by performing principal component analysis (PCA) on LS and SS measurements separately and correlation analysis between LS and SS components. The auxiliary measurements of triaxial acceleration, respiration and pulsation were bandpass filtered with 0.008 Hz - 0.2 Hz and then detrended by a third-order polynomial drift. The detrended auxiliary measurements and a third-order polynomial drift, a clenching regressor were included in the design matrix.

D. Block Averages and Topographies

For experiment 1, the block averages were calculated by removing the baseline (i.e., mean amplitude of -5 to 0 s to the onset of each block) and calculating the mean and standard error across six blocks. The topographies displayed the mean amplitudes across 5 to 15 s of the block averages of all LS channels.

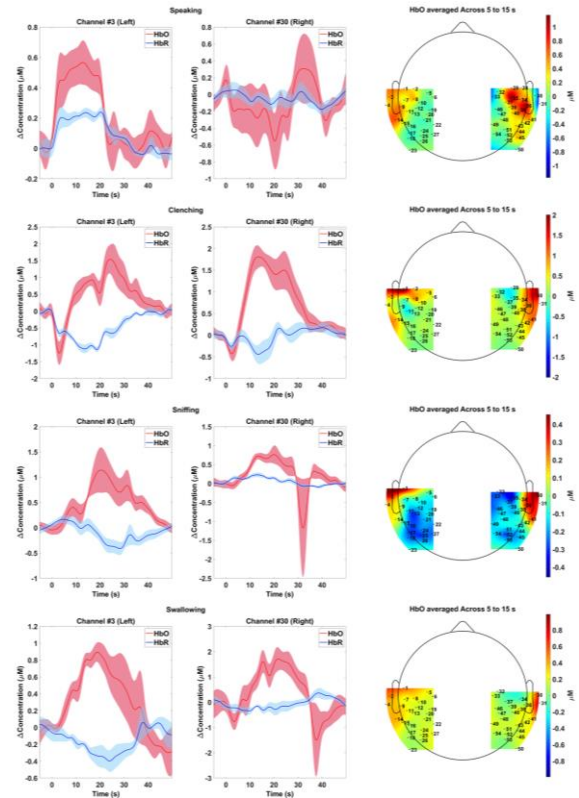


Figure 1. Movement-related signals in a representative subject. The block averages of HbO and HbR responses are observed in clenching channels (left and middle columns) and topographies (right column) in four movements, i.e., speaking, clenching, sniffing, and swallowing. The shaded areas represent the standard error across blocks.

E. Validation of PCA-GLM

The beta value of the clenching regressor represents the jaw-clenching effect. To determine whether PCA-GLM reduces the motion artifacts associated with jaw clenching, we perform a one-sided, paired-sample t-test on the beta values of the clenching channel of No Correction and PCA-GLM conditions.

III. RESULTS

A. Motion Artifacts due to Four Types of Jaw Movements

Fig. 1 demonstrates the block averages and topographies from a representative subject in four conditions of jaw movements. Across four types of jaw movements, a pair of symmetric channels (channels #3 on the left side and #30 on the right side) located over the temporal muscles were identified to exhibit task-like activations, which could be misinterpreted as spurious auditory responses. Channel #3 shows an increase in HbO and a decrease in HbR in all conditions except speaking. Channel #30 exhibits an increase in HbO and a decrease in HbR in clenching and swallowing conditions. Among the four conditions, the jaw clenching condition depicts larger and more consistent artifacts that resemble hemodynamic response across subjects. Therefore, we chose to focus on jaw clenching in Experiment 2 with a larger sample size, to further investigate the effects of jaw clenching and the efficacy of PCA-GLM in reducing motion artifacts induced by jaw clenching.

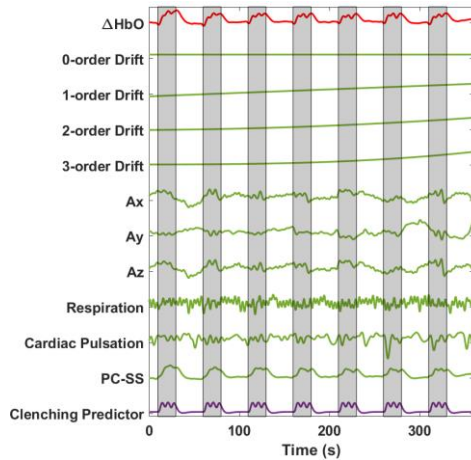


Figure 2. Relative concentration changes in a LS channel, 3-order drift, nuisance regressors from auxiliary measurements, the noise component PC-SS, and Clenching predictor. Both fNIRS and auxiliary measurements were band-pass filtered with 0.008 Hz – 0.2 Hz. Shaded areas correspond to the clenching periods.

B. Efficacy of PCA-GLM

In order to address the jaw movement-related artifacts, we have investigated the PCA-GLM method [7]. Fig. 2 shows the time courses of signals and nuisances in the GLM constructed for denoising, including the HbO full time course of channel #3, nuisance regressors (including the third-order polynomial drift, triaxial acceleration, respiration, cardiac pulsation, and PC-SS) and clenching HRF regressor which accounts for the clenching effects. The HbO full time course exhibits an increase along with some ripples with smaller amplitudes during the clenching period and a decrease during the resting period. The superficial global component, i.e., PC-SS, very

well depicts the general trend of increases and decreases following the block design.

Fig. 3 shows the block averages of HbO and HbR in channels #3 and #30 after No Correction and PCA-GLM. With No Correction, the block averages depict a task-like increase and decrease in HbO and HbR with a larger amplitude compared to normal hemodynamic response. After applying PCA-GLM, the block averages exhibit much smaller increasing or decreasing responses in HbO/HbR.

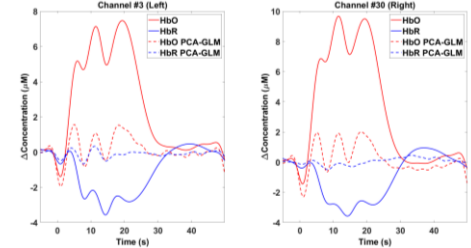


Figure 3. Session-level comparison of HbO (red) and HbR (blue) block averages with No Correction (solid lines) and PCA-GLM (dashed lines).

Fig. 4 demonstrates the denoising effect at a group level. The beta values of the clenching regressor of HbR in the clenching channel are significantly lower in PCA-GLM compared with No Correction ($p = 0.036$). In HbO, a similar trend was observed but the difference between PCA-GLM and No Correction was approaching significance ($p = 0.06$). The PC-SS regressor in PCA-GLM very well matches the overall trend of HbO and HbR fluctuations due to the jaw movements, and thus serves to attenuate the task-like responses induced by the jaw clenching.

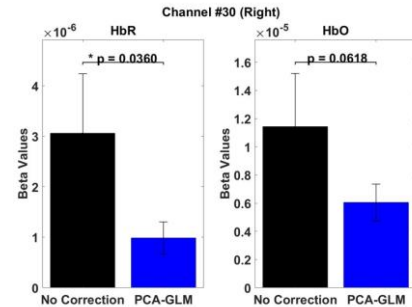


Figure 4. Bar graphs of beta values of clenching regressors of HbO and HbR in the clenching channel. The error bar indicates the standard error across subjects. The asterisks above lines indicate statistically significant differences between No Correction and PCA-GLM.

IV. DISCUSSION

This present study has shown that motion artifacts in fNIRS signals that resemble task-evoked responses are induced by jaw movements including speaking, clenching, swallowing, and sniffing. More importantly, we have demonstrated that our previously established pipeline namely PCA-GLM can reduce the motion artifacts related to jaw movements.

In Experiment 1, our results (Fig.1) showed that all four types of jaw movements could introduce artifacts resembling task-evoked activations into fNIRS signals. Particularly, the jaw clenching introduced a task-activation-like increase and decrease in HbO and HbR respectively in a pair of symmetric

channels located at the temporal cortex, which may be misinterpreted as spurious auditory responses. The results are consistent with the previous with previous literature [11]. Moreover, our study has shown the artifacts associated with four various types of movements (i.e., speaking, clenching, sniffing, and swallowing), which may occur involuntarily during fNIRS recordings.

In experiment 2, we demonstrated that our previously reported PCA-GLM method can effectively reduce the jaw-clenching movement artifacts, as shown in Fig. 4 the beta values of the clenching regressor were significantly lower in HbR and approaching significantly lower in HbO after PCA-GLM compared to No Correction. As an example, the PC-SS very well catches the overall trend of HbO in a representative subject (Fig. 2) and therefore has accounted for the nuisance variances due to jaw clenching. The amplitudes of an increase and decrease in HbO and HbR respectively during the clenching period were reduced sharply after PCA-GLM (Fig. 3). Further investigation on the temporal and spatial characteristics of different types of jaw movements as well as developments of denoising methods may help to improve the sensitivity and accuracy of fNIRS signals in auditory and language processing.

V. CONCLUSION

The outcomes of the present study have underlined the importance of addressing motion artifacts related to jaw movements in fNIRS recordings. Four types of jaw movements (speaking, clenching, sniffing, and swallowing) could introduce task-like activations in fNIRS signals, which can potentially lead to misleading results. Furthermore, we have shown the PCA-GLM method is an effective approach for reducing the motion artifacts induced by jaw clenching.

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