Co-registration of brain activation from concurrent fNIRS and fMRI during hand exoskeleton use towards monitoring neurorehabilitation

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INTRODUCTION

Injuries to the brain such as stroke and traumatic brain injury can cause physical impairments of the motor system, such as hemiparesis, or partial paralysis. Lasting motor deficits such as hand impairment can make it challenging to perform daily living tasks. Assistive and rehabilitative robotics can be used to restore function or engage the brain's neuroplasticity towards regaining motor control [1]. In order to optimize the design of upper limb exoskeletons for the promotion of motor relearning, it is valuable to measure brain activation. Portable neuroimaging techniques like functional near-infrared spectroscopy (fNIRS) can be used to monitor neurorehabilitation following brain injuries, which could be useful for evaluating assistive and rehabilitative technology like a hand exoskeleton. However, the spatial precision and resolution of fNIRS is limited without an anatomical reference, compared to functional magnetic resonance imaging (fMRI) which has high spatial resolution and precision.

Both fMRI and fNIRS measure changes in blood oxygenation, also known as the hemodynamic response. Collecting fMRI and fNIRS concurrently provides an anatomical reference and a trusted brain activation map from the fMRI for comparison and validation of fNIRS data. We present a co-registration method using 3D Slicer to align and overlay brain activation data from both neuroimaging modalities, allowing researchers to compare brain activation maps with respect to each subject's anatomical brain. This approach demonstrates how the relation between fMRI and fNIRS data can enable neurorehabilitation monitoring using fNIRS with increased spatial understanding.

MATERIALS AND METHODS

A study was conducted to capture brain activation from fNIRS and fMRI simultaneously during hand motor tasks. This study was approved by the Worcester Polytechnic Institute's institutional review board (HHS #00007374). Five control subjects (4 male, 1 female; 30 ± 9 y.o.) were recruited from the student and staff population at Worcester Polytechnic Institute. Subjects had no neurological or muscular injuries/conditions. All subjects showed no contraindication for being in the MRI scanner. All subjects except 1 male were right-handed. All subjects were native English speakers.

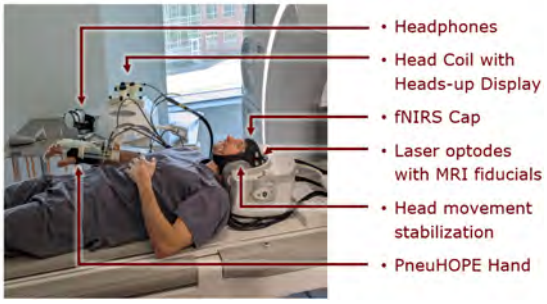

Fig. 1 Experimental set-up showing a subject on the MRI bed with the PneuHOPE Hand attached to their right arm, an fNIRS cap placed on their head, and additional MRI compatible equipment.

An MRI scanner (SIGNA Premier 3.0T Scanner by GE Healthcare) was used to collect structural images (T1 weighted scans) and capture brain activation, using fMRI scan sequences, through measurement of the blood oxygenation-level dependent (BOLD) signal. A NIRScout fNIRS system (NIRx, Berlin, Germany) was used to collect brain activation data using an 8x8 montage of laser optodes in a cap worn on the head. Laser optodes were chosen for their MRI compatibility. Two montages, or optode configurations, were used in this study to test different coverage options. Both montages consist of 20 source-detector pairs, resulting in 20 channels of data, each reporting changes in light absorption at two wavelengths, one for de-oxygenated hemoglobin concentration changes, and the other for oxygenated hemoglobin concentration changes. Fiducials were placed on the fNIRS optodes to identify their location with respect to the anatomical brain in 3D space using MRI.

The PneuHOPE Hand, an MRI compatible hand exoskeleton designed for individuals with spastic hand impairment following an upper motor neuron injury, was used to facilitate hand movement, and worn throughout the study [2]. A NordicNeuroLab heads-up display was used in this

study to display visual prompts which instruct the subjects in performing the study tasks. The experimental set-up can be seen in Figure 1.

Subjects were asked to complete two tasks during their study session, 1) finger tapping, and 2) exoskeleton facilitated hand movement with active collaboration. Each trial consisted of four 30-second active blocks and five alternating 30-second rest blocks. This block paradigm was used to define the expected time course of brain activation.

Standard pre-processing was performed on both fMRI and fNIRS data, then a generalized linear model (GLM) was created using the hemodynamic response function for both fNIRS and fMRI data, to fit the brain activation data to the active task blocks. Statistical parametric mapping (SPM) was used on the fNIRS data to create a brain activation map consisting of 20 channels across the montage, performed in nirsLab (NIRx, Berlin, Germany). A cluster analysis was performed on the fMRI data to generate cluster volumes of activation using FEAT analysis in FMRIB Software Library (FSL) [3]. Significant activation from both fMRI and fNIRS data is determined with $p < .05$.

A high resolution MRI structural scan was segmented in 3D Slicer to generate a subject-specific brain model, as well as a model of the fiducials marking the fNIRS optode locations. A lower resolution brain segmentation was generated using the fMRI scan. The activation volume was also segmented to generate a model. All of these models can be seen in Figure 2A. Significant activation measured by the simultaneous fNIRS system is shown on a generic brain with colored channels that are located based on assumed optodes locations (seen in Fig. 2B. This generic model and assumed optode spacing may be inaccurate with respect to each subject's anatomical brain and activated region. Channel segmentations were created in 3D Slicer, using the accurate fiducial locations, and colored to represent the intensity of the activation of each channel from the fNIRS data. Figure 2C displays the fNIRS data visually overlaid on the anatomical brain so it can now be compared to the activation captured by the fMRI.

RESULTS

A pipeline for co-registering fNIRS and fMRI data was presented and data was collected in a preliminary study. Brain data from fNIRS can be accurately translated into the subjects' anatomical coordinate system to compare with the brain anatomy and fMRI data.

DISCUSSION

Spatial assumptions made with fNIRS alone can make it challenging to interpret brain data with respect to the anatomical brain structure and function, especially after brain injury, making it challenging to monitor neurorehabilitation. This preliminary study, the presented co-registration pipeline and the resulting overlaid brain activation maps provide context for the fNIRS data, enabling confident collection of anatomically relevant

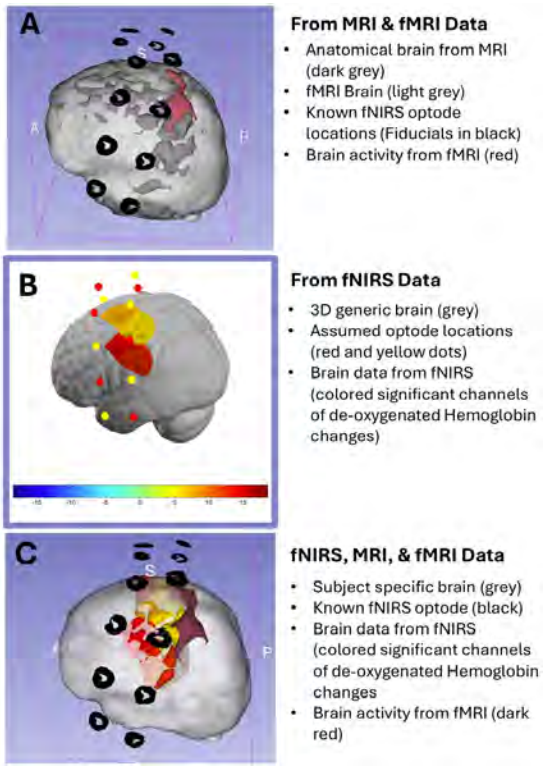

Fig. 2 A) Neuroimaging data from MRI and fMRI in 3D Slicer, B) Neuroimaging data from fNIRS shown on generic brain with assumed optode locations, C) Neuroimaging data from fMRI and fNIRS overlaid in 3D Slicer with respect to anatomical brain from MRI. Task: finger tapping.

fNIRS data in subsequent studies to monitor neurorehabilitation during hand exoskeleton use. This pipeline could be used to create subject-specific fNIRS montages for individuals with brain injuries to ensure spatial relevance during longitudinal studies that use low-density fNIRS alone for portable neuroimaging.

Using fiducials to co-locate points with the MRI is a common technique in surgical robotics for robot registration. 3D Slicer is commonly used in surgical planning for visualizing critical brain structures in preparation for surgery. The presented pipeline could also be used to capture critical functional volumes in the brain to avoid during surgery. For example, language tasks can be used to identify cortical areas necessary for speech and language comprehension, which can then be avoided during surgery.

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