Dynamic causal modeling for EEG during complex laparoscopic skill acquisition

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ABSTRACT

Fundamentals of Laparoscopic Surgery (FLS) is a prerequisite for board certification in general surgery in the USA. It includes a motor skills portion with five psychomotor tasks of increasing task complexity: (i) pegboard transfers, (ii) pattern cutting, (iii) placement of a ligating loop, (iv) suturing with extracorporeal knot tying, and (v) suturing with intracorporal knot tying. Learning these tasks typically relies on extensive practice [1] that may be facilitated with transcranial electrical stimulation (tES) [2]. However, tES needs to be directed at the brain network that underpins laparoscopic skill acquisition [2]. Nemani et al. [3] showed that the wavelet coherence based functional connectivity from functional near-infrared spectroscopy (fNIRS) between the medial prefrontal cortex (PFC) and the supplementary motor area (SMA) was lower for experts than novices during FLS pattern cutting task. Here, the extended frontal aslant tract (exFAT) [2] may be leveraged by novices since SMA is known for the plasticity of interhemispheric connectivity involving sensorimotor network [4] relevant in bimanual tasks [5],[6],[7],[8]. However, transcranial direct current (tDCS) of the SMA resulted in more variability during FLS pegboard transfers than tDCS of bilateral primary motor cortex (M1)[9] which may be related to inter-individual differences in tDCS effects on pre-SMA versus SMA proper in the SMA complex [10]. Furthermore, motor task complexity may be relevant [2] where prior work on most complex FLS suturing task with intracorporeal knot tying [11] showed the involvement of premotor/frontal module [10] related Brodmann areas (BA), shown in Figure 1c, including ventrolateral PFC (VLPFC; BA: 44, 45, 47), frontopolar (FP; BA: 10), dorsolateral PFC (DLPFC; BA: 9, 46) as well as a part of the orbitofrontal cortex (OFC; BA: 11) on the lateral brain surface in addition to SMA complex. This may be related to the involvement of the superior longitudinal fascicle (SLF) [10]; however, the effective connectivity via various frontal lobe connections [10] was not investigated based on dynamic causal modeling (DCM)[12]. Here, the temporal resolution of electroencephalogram (EEG) can capture fast interactions expected via short frontal lobe connections [10].

Methods: The study was approved by the Institutional Review Board of the University at Buffalo. Eight right-handed novice subjects (age: 22-32 years) performed the FLS suturing with intracorporal knot tying for the first time using an FLS-certified physical trainer box. The experimental setup is shown in Figure 1a. The session consisted of a block design of 2 min rest and a FLS task (stimulus) period – 3 min for the experts and 10 min for the novices. EEG imaging was conducted at 500Hz using wireless LiveAmp (Brain Products, USA) during three repeated blocks of rest and stimulus for each subject. Our EEG electrode montage consisted of 32 channels that covered the prefrontal and sensorimotor brain areas, as shown by Figure 1b.

Data processing was conducted using the open-source EEGlab toolbox [13] in Matlab (Mathworks Inc., USA). The raw data were first downsampled to 250Hz. Then, a high-pass filter was applied to the data at 1-Hz. Then, the line noise was removed using the "CleanLine" function. Then, we applied the function "clean_rawdata()" to reject bad channels and interpolated the removed channels (maximum 5). We then referenced the data to average and applied "clean_rawdata()" function to perform Artifact Subspace Reconstruction (ASR). ASR processing is essential to remove movement-related artifacts balancing between removing non-brain signals and retaining brain activities [14]. Then, we re-referenced the data to average. We then performed independent component (IC) analysis (ICA) using "runica" function and localized the dipoles using "dipfit" function [15]. We used the default head model settings in the EEGlab toolbox [13] for the dipole localization. The brain-related ICs were identified based on the dipole location in the brain and then were subjected to DCM in the open-source SPM12 toolbox [16]. DCM was applied to all frontal lobe connections (exFAT, SLF) [10] based on our prior work [17] – Figure 2a shows the directed functional network based on time-varying Granger causality using EEG channel data (same dataset and preprocessing as described above in EEGlab) that was significantly ($p<0.05$) different between experts and novices.

Results: In Figure 2a, the left PFC(LPFC) node includes EEG channels overlying the left DLPFC and VLPFC and then vice versa for the right PFC (RPFC) node. Also, the SMA node includes the EEG channels overlying the SMA complex, while the LM1 node includes EEG channels overlying left sensorimotor areas, including M1, premotor cortex, and parietal cortex and vice versa for the RM1 node. We investigated all frontal lobe connections [10] of superficial (cortical) IC sources related to the nodes in Figure 2a using DCM. Figure 2b shows the posthoc selection [18], where the left frontoparietal network (FPN) was found to be most evident during the whole task duration (constant IC model) in novices. Here, IC related to the frontal theta activity that was localized at the left DLPFC while the IC localized at the centroparietal regions is postulated to be the sensorimotor *mu* rhythm and the Figure 2c shows the effective connectivity found from DCM. The Figure 2d shows the ICs at the medial frontal cortex (left panel) and parietal lobe (right panel); however, medial frontal cortex node was not consistent [19] across novices.

Discussion: We showed the feasibility of an EEG-based DCM approach to elucidate the brain networks during complex FLS suturing task in right-handed novices that was found left lateralized (SLFI?[20],[21]). We found that the novices mostly had the node at the pre-SMA while experts showed more SMA proper node – (exFAT?[10]) needs further investigation. Then, the relevance of the DLPFC node in all the novices can be related to attentional control (FPN) necessary during skill learning [22]. Ashcroft et al. [23] found that tDCS of DLPFC (BA 9) improved performance score in an open surgery knot-tying task. However, that surgical task can be considered less complex than the FLS suturing task in this study. Here, we postulate based on prior work [24] that transcranial alternating current stimulation targeting the left FPN (SLFI[20],[21]) may be more effective for FLS suturing task with neuroimaging-guided transcranial electrical stimulation [11].

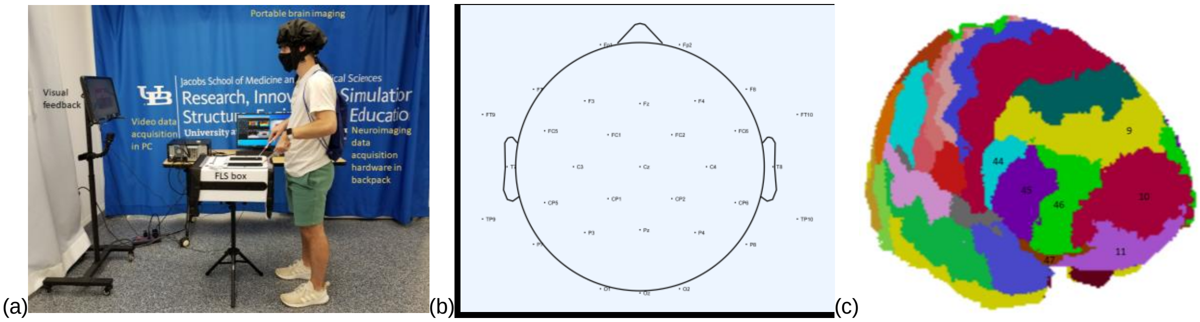

Figure 1: (a): Experimental setup. (b): EEG electrode montage. (c) Premotor/frontal module related Brodmann areas.

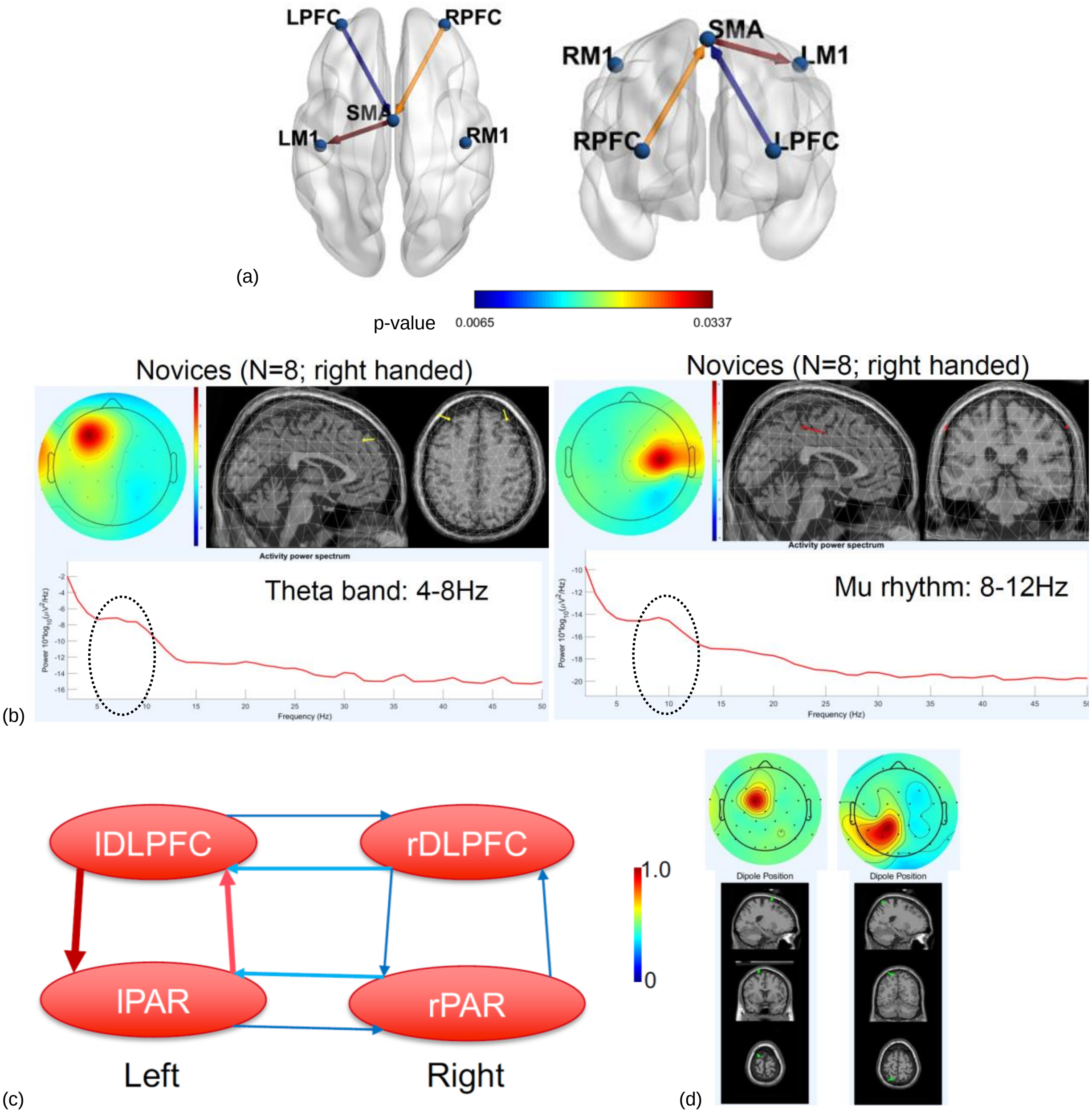

Figure 2. (a) Directed functional network based on time-varying Granger causality using EEG channel data. LPFC: left prefrontal cortex. RPFC: right prefrontal cortex. SMA: supplementary motor complex. LM1: left sensorimotor area. RM1: right sensorimotor area. (b) Cortical independent components (ICs) found in novices (N=8). (c) Dynamic causal modeling results using cortical ICs where left frontoparietal network was found to be most active in novices during the whole task duration (connection strength shown by the color bar). (d) Illustrative dipole locations at medial frontal cortex (left panel) and parietal lobe (right panel).

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