2021 43rd Annual International Conference of the
IEEE Engineering in Medicine & Biology Society (EMBC)
Oct 31 - Nov 4, 2021. Virtual Conference

Neuroimaging guided tES to facilitate complex laparoscopic surgical tasks – insights from functional near-infrared spectroscopy

Pushpinder Walia, Yaoyu Fu, Steven D. Schwaitzberg, Xavier Intes, Suvranu De, Lora Cavuoto, Anirban Dutta

***Abstract*—Fundamentals of Laparoscopic Surgery (FLS) is a prerequisite for board certification in general surgery in the USA. In FLS, the suturing task with intracorporeal knot tying is considered the most complex task. Transcranial direct current stimulation (tDCS) of the dorsolateral prefrontal cortex (PFC) has been shown to facilitate FLS surgical skill acquisition where 2mA tDCS for 15min with the anode over F3 (10/10 EEG montage) and cathode over F4 has improved performance score in an open knot-tying task. Since PFC has a functional organization related to the hierarchy of cognitive control, we performed functional near-infrared spectroscopy (fNIRS) to investigate PFC sub-domain activation during a more complex FLS suturing task with intracorporeal knot tying. We performed fNIRS-based analysis using AtlasViewer software on two expert surgeons and four novice medical students. We found an average cortical activation mainly at the left frontopolar PFC across the experts, while the average cortical activation across the novices was primarily at the left pars opercularis of the inferior frontal gyrus and ventral premotor cortex, inferior parietal lobule, and supramarginal gyrus. Here, the average cortical activation across the novices included not only the cognitive control related brain regions but also motor control complexity related brain regions. Therefore, we present a computational pipeline to identify a 4x1 high-definition (HD) tDCS montage of motor complexity related PFC sub-regions using ROAST software.**

***Clinical Relevance*—A computational pipeline for fNIRS-guided tES to individualize electrode montage that may facilitate FLS surgical training in our future studies.**

I. Introduction

The 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 intracorporeal knot tying. Learning these tasks typically relies on extensive practice, where trainees repeat the task tens to hundreds of times to reach proficiency [1]. Recent brain imaging studies for the pattern cutting task have shown that novices exhibit elevated levels of prefrontal cortex (PFC) activation compared to experts [1]. This is consistent with the motor learning literature, which has shown that early skill acquisition depends on the PFC. Transcranial direct current stimulation (tDCS) has been proposed as a means of facilitating training efficiency for these surgical skills [2]. A recent study demonstrated the feasibility of PFC tDCS to facilitate early-phase surgical-skill acquisition [3]. Indeed, PFC activation is expected in the early phase of skill acquisition when attention and working memory are required to actively monitor the tool and the targets in the environment until 'automaticity' is achieved for the visuomotor control of the tool. Ashcroft et al. [3] used a one-size-fits-all approach with the anode over F3 (10/10 EEG montage) and cathode over F4 to deliver 2mA tDCS for 15min, resulting in an improved performance score in an open surgery knot-tying task (three repeated blocks) when compared to sham tDCS. Here, F3-F4 tDCS was postulated to target the cognitive associative network via the dorsolateral PFC node.

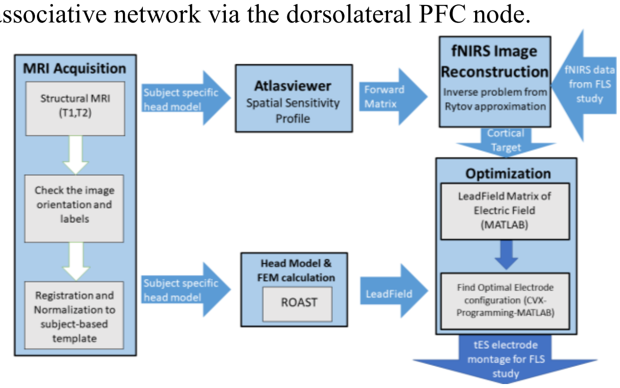

Fig. 1: Proposed neuroimaging guided transcranial electrical stimulation. "Colin27" digital brain MRI atlas was used for head modeling in the current study.

Our prior work [1] has shown that PFC activation decreased with an increase in the motor skill proficiency, while fine motor skill control-related brain regions showed increased activation for experts as expected [4]. However, the hierarchy of cognitive control was not investigated vis-à-vis a rostrocaudal gradient in the sub-regions of PFC [5]. Here, a shift from posterior-to-anterior is postulated to mediate progressively abstract, higher-order control [5] even though executive control may operate as a unitary function [6]. We postulated that this would be more relevant in the case of the FLS suturing task with intracorporeal knot tying that is considered the most complex FLS task. In this paper, we present a portable neuroimaging guided tDCS approach to monitor and facilitate subject-specific sub-regional PFC activation during FLS task performance that is postulated to be more effective in facilitating surgical-skill acquisition than

The authors gratefully acknowledge the support of this work through the Medical Technology Enterprise Consortium (MTEC) award #W81XWH2090019 (2020-628), and the U.S. Army Futures Command, Combat Capabilities Development Command Soldier Center STTC cooperative research agreement #W912CG-21-2-0001.

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978-1-7281-1178-0/21/$31.00 ©2021 IEEE

the "one-size-fits-all" approach used by Ashcroft et al. [3]. Fig. 1. shows our computational pipeline [7] using open-source pipelines (ROAST [8] and AtlasViewer [9]) where age-specific magnetic resonance imaging (MRI) templates can be used for head modeling [10] when subject-specific MRI data is unavailable. Subject-specific brain regions related to motor complexity of the FLS task can be identified with functional near-infrared spectroscopy (fNIRS) [11].

Subject-specific brain response to motor complexity is an important area of investigation [11]. Motor complexity sensitive brain regions may be relevant in surgical training, viz. complex FLS suturing task with intracorporeal knot tying may require attentional control in the inferior frontal gyrus [12] and polymodal processing in the ventral premotor cortex [13],[14]. Since fNIRS has been shown feasible during surgical task performance [1],[15], we conducted a case series with two expert surgeons and four novice medical students to elucidate PFC sub-regional activation during suturing task.

II. Methods

A. Case Series

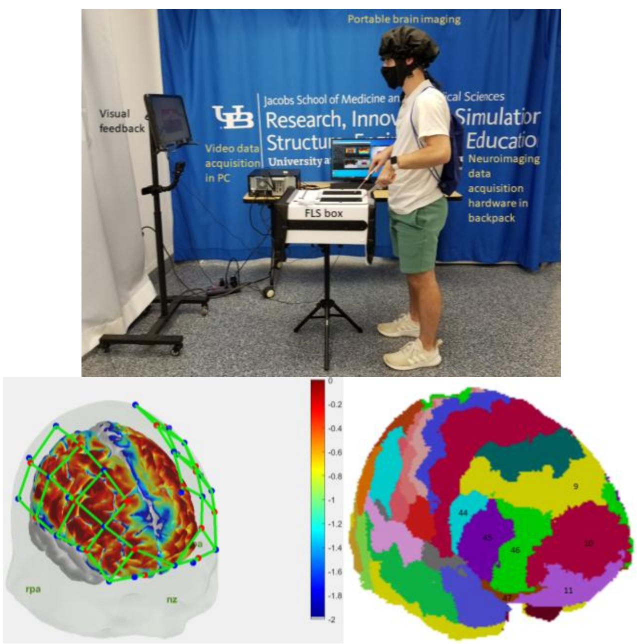

Fig. 2: Top panel: Experimental setup. Bottom panel: fNIRS sensitivity profile(left) and cognition related Brodmann areas(right)

The study was approved by the Institutional Review Board of the University at Buffalo. Two right-handed expert surgeons (age: 56 years and 37 years) with more than 3 years of laparoscopic surgical experience participated in the FLS suturing study. In addition, four right-handed novice subjects (age: 22-28 years) performed the FLS suturing task for the first time using an FLS-certified physical trainer box. The experimental setup is shown in the top panel of Fig. 2. The session consisted of a block design of 2 min rest and a stimulus period, 3 min for the experts and 10min for the novices, where the FLS suturing task was performed until completion. fNIRS imaging was conducted using NIRSPORT 2 (NIRx, USA) during three repeated blocks of rest and stimulus for each subject. Our fNIRS optode montage consisted of 16 long-separation (~3.5cm) sources, 15 long-separation (~3.5cm) detectors, and 8 short-separation (<1cm) detectors that covered prefrontal and sensorimotor brain areas as shown by fNIRS sensitivity profile [9] in bottom panel of Fig. 2. Bottom panel shows cognition related Brodmann areas (BA): ventrolateral PFC (BA: 44, 45, 47), frontopolar/orbitofrontal PFC (BA: 10, 11), and dorsolateral/medial PFC (BA: 9, 46) [16].

B. Portable neuroimaging data processing

Data processing was conducted using the open-source HOMER3 toolbox [17] in Matlab (Mathworks Inc., USA). The raw optical intensity signal was first converted into optical density (function: hmrR_Intensity2OD), then motion artifact detection and correction was conducted using a hybrid method based on a spline interpolation method and Savitzky–Golay filtering (function: hmrR_MotionCorrectSplineSG) [18] using default parameters. Then, bandpass filtering was conducted (function:hmrR_BandpassFilt:Bandpass_Filter_OpticalDensity) within 0.01-0.1Hz followed by conversion to oxy-hemoglobin (HbO) and deoxy-hemoglobin (HHb) concentration with default partial path-length factor (function: hmrR_OD2Conc). Finally, short-separation (SS) regression was performed before computing the hemodynamic response function (HRF) using General Linear Model (GLM) (function: hmrR_GLM_new). GLM was performed to determine the HRF during the stimulation period from the resting state using ordinary least squares [19] with the consecutive sequence of Gaussian functions (stdev=0.5, step=0.5) along with SS regression with the average of all SS channels. Then, we used open-source AtlasViewer [9] in Matlab (Mathworks Inc., USA) to determine cortical activation for the HRF. We used default "Colin27" brain atlas for the HRF image reconstruction based on optode sensitivity profile in the log10scale (Fig. 2) with the regularization scaling parameter = 0.01.

C. Neuroimaging-guided transcranial electrical stimulation

The centroid of the cortical activation was found by calculating the average position in the activation "mass" weighted by the image intensity [9]. This centroid was used after mapping to the MNI-152 standard head [20] for targeting transcranial electric stimulation (tES) using an open-source ROAST pipeline [8]. Fig. 1 shows the block diagram for subject-specific neuroimaging guided tES where a single function ("roast_target") was used for the optimization under criteria, maximal-intensity or maximal-focality using the "MNI152" based lead-field matrix and default parameters. We limited 4x1 high-definition (HD) tDCS montage where the total injected current cannot exceed 4 mA (in StarStim 8).

III. Results

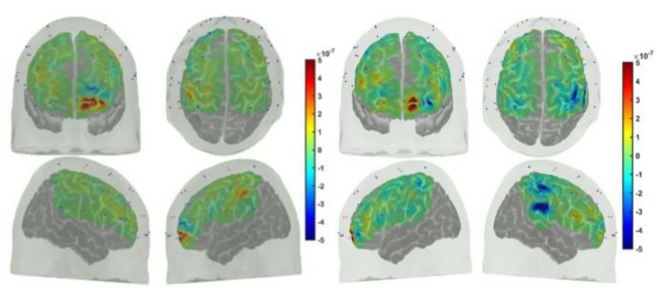

Fig. 1: Cortical activation (HbO color bar ±5E-7 M) during FLS suturing task. Left panel for Expert 01 and right panel for Expert 02.

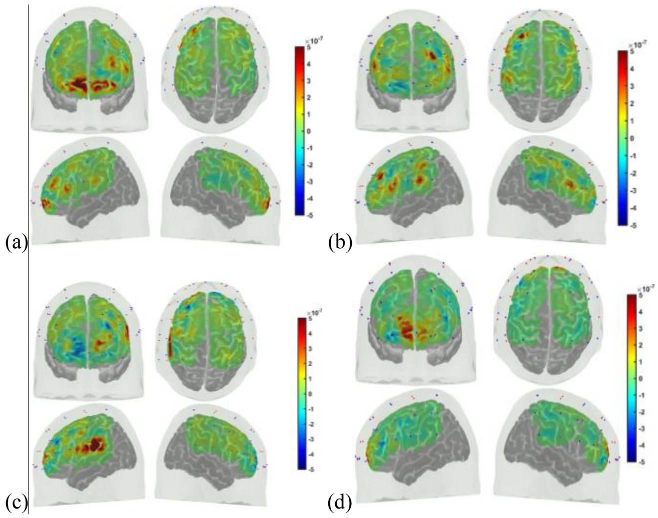

Fig. 4: Cortical activation (HbO color bar ±5E-7 M) during FLS suturing task for the four novices (a to d).

Completion of the FLS suturing task led to cortical activation in terms of average task-related HbO changes from baseline primarily at the left lateral frontopolar prefrontal cortex in the experts, as shown in Fig. 3. Also, greater cortical activation at the left than the right sensorimotor cortex was found for the right-handed experts. In novices, inter-subject variability in the average task-related cortical activation was found, as shown in the panels of Fig. 4. As seen in Fig. 4, two subjects (Fig. 4a, d) mainly had bilateral frontopolar prefrontal cortex activation. Also, three (Fig. 4a-c) out of four novices had cortical activation mainly at the ventrolateral PFC, including the left pars opercularis of the inferior frontal gyrus as well as the ventral premotor cortex, inferior parietal lobule, and supramarginal gyrus. The left pars opercularis of the inferior frontal gyrus, ventral premotor cortex, inferior parietal lobule, and the supramarginal gyrus are considered brain regions sensitive to motor complexity [11].

Fig. 5 shows the average cortical activation across the experts (left) and the novices (right), where the left lateral frontopolar prefrontal cortex was mainly active across experts in addition to the frontoparietal areas. The primary cortical activation across novices was at the supramarginal gyrus (BA: 40) with extension to the inferior frontal gyrus (BA: 44, 45), left dorsolateral PFC (BA: 46), ventral premotor cortex, inferior parietal lobule that have been shown sensitive to motor complexity [11].

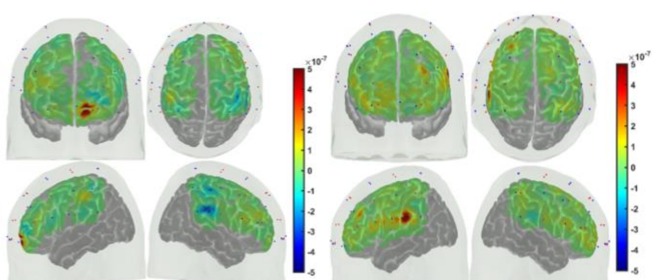

Fig. 5: Average cortical activation (HbO color bar ±5E-7 M) during FLS suturing across experts (left panel) and novices (right panel).

Fig. 6a shows the contrast between the average activation in the novices and the experts. Here, the electric field distribution due to 2mA tDCS at the F3-F4 (10/20 EEG locations) from Ashcroft et al. [3] targeted the dorsolateral PFC primarily (BA 9), as shown in Fig. 6b. Since we found that three (Fig. 4a-c) out of four novices also had cortical activation at the ventrolateral PFC, including the left pars opercularis of inferior frontal gyrus relevant in complex motor control [11]; therefore, we applied our computational pipeline for neuroimaging guided tES (top panel Fig. 1) to target the left PFC brain regions, BA 44-46, sensitive to motor complexity [11] using 4x1 HD-tDCS, as shown in Fig. 6c.

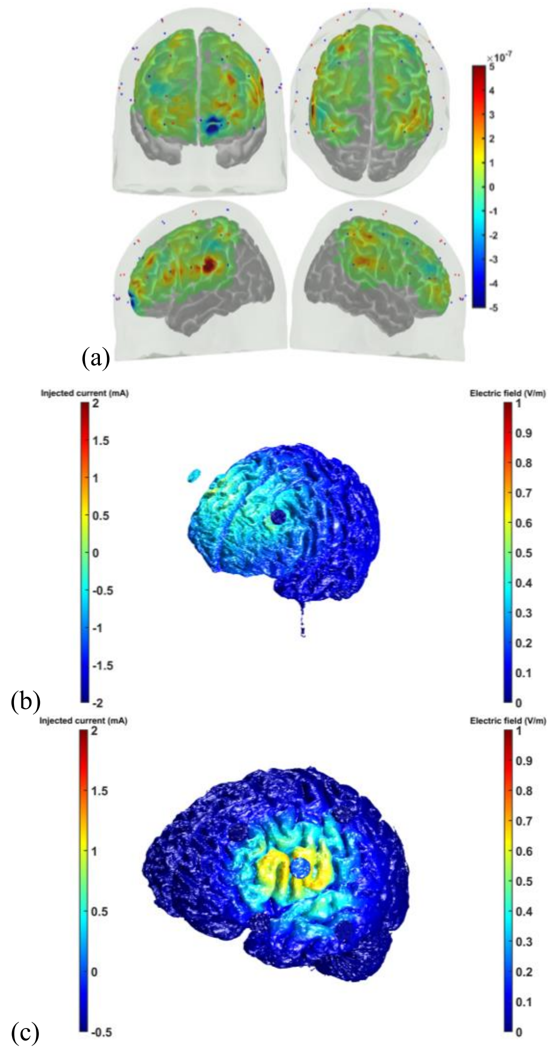

Fig. 6: (a) Contrast between the average cortical activation (HbO color bar ±5E-7 M) in the novices and the experts. (b) Electric field distribution of the 2mA tDCS at F3-F4. (c) Electric field distribution of the neuroimaging guided 2mA 4x1 HD-tDCS montage for Brodmann areas 44-46.

IV. Discussion

In this preliminary study, we developed a computational pipeline for fNIRS-guided tES that is postulated to facilitate complex FLS suturing task with intracorporeal knot tying. In a cohort of two expert surgeons and four novice medical students, we found greater activation (see Fig. 6a) of brain regions sensitive to motor complexity [11] in novices when compared to experts. In the experts, the primary cortical activation was at the left lateral frontopolar PFC (see Fig. 5), which can be related to abstract second-order relationships during cognitive control [5]. In contrast, dorsolateral and ventrolateral PFC activation (see Fig. 5) in the novices can be related to feature extraction and forming first-order relationships in cognitive control [5]. We investigated the electric field distribution for the tDCS montage used by Ashcroft et al. [3] that was found to target the dorsolateral PFC (BA 9)– see Fig. 6b. This tDCS montage was found to improve performance score in an open surgery knot-tying task that can be considered less complex than the FLS suturing task with intracorporeal knot tying. In this study, we found activation of brain regions sensitive to motor complexity [11], including BA 44-46, so we investigated the feasibility of a 4x1 HD-tDCS montage in simulation in ROAST [8] as shown in Fig. 6c. We postulate that our 4x1 HD-tDCS montage targeting the PFC brain regions sensitive to motor complexity [11] will be more effective for more complex FLS tasks than the tDCS montage used by Ashcroft et al. [3] that primarily targeted BA 9.

Future studies need to investigate subject-specific brain response to the complexity of the motor task, i.e., the brain-behavior relationship, that can be used to individualize tDCS electrode montage. This is crucial in novices due to their inter-individual differences in the cortical activation, as shown in Fig. 4. Here, bilateral frontopolar PFC activation in two novices (Fig. 4a,d) can be related to higher-order cognitive control while other two novices (Fig. 4b,c) were still forming first-order relationships [5] during FLS suturing task. This can be explained by many theories on the functional organization of PFC [16] where PFC has been consistently related to the temporal organization of goal-directed behavior. This top-down selection and biasing of control based on the task demands and goals is crucial during surgery. Here, the executive control may operate as a unitary function [6]; however, the information flows within the functional sub-regions of PFC and their interactions with the secondary somatosensory areas [21] may be crucial. Therefore, our next step is to elucidate the evolution of inter-regional brain connectivity during the FLS suturing task where our prior work [15] identified functional brain connectivity related to surgical skill dexterity during FLS pattern cutting task. Our preliminary study was limited by a small number of subjects and "Colin27" brain atlas for head modeling; although, both ROAST and AtlasViewer allowed subject-specific MRI-based head modeling [22] which will be applied in the future.

V. Conclusion

We developed a computational pipeline for fNIRS-guided tES that highlighted the importance of targeting the brain regions sensitive to motor complexity in novices during FLS suturing task with intracorporeal knot tying.

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