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Prefrontal transcranial direct-current stimulation improves early technical skills in surgery

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ABSTRACT

Background: Studies applying transcranial direct-current stimulation (tDCS) to motor regions to enhance surgical skills have observed modest benefits in performance. Early surgical skills acquisition is known to be dependent on the prefrontal cortex (PFC) which could be a suitable target for performance enhancement in fields with high cognitive demand.

Objective: To assess whether prefrontal tDCS could improve early phases of surgical skill development.

Methods: In a randomized sham-controlled double-blind parallel design, 40 surgical novices performed an open knot-tying task repeated in three blocks; pre-, online- and post-tDCS. During online stimulation, participants were randomized to either active tDCS (2 mA for 15 min) to the prefrontal cortex (anode over F3, cathode over F4) or sham tDCS. Performance score (PS) was computed using a validated algorithm and introspective workload domains were assessed using a SURG-TLX questionnaire.

Results: There was no difference in demographics or PS between groups prior to receiving tDCS. PS significantly improved from pre-to online- ($p < 0.001$) and from pre-to post-tDCS ($p < 0.001$) in the active group only. Following active tDCS, PS was closer to the defined proficiency benchmark and significantly greater compared to sham ($p = 0.002$). Only the active group reported significantly improved temporal demand scores from pre-to online- ($p = 0.004$) to post-tDCS ($p = 0.002$).

Conclusions: This study demonstrates significantly improved early phase surgical-skill acquisition following prefrontal tDCS. Further work is required to determine the underlying neurophysiological mechanisms and whether the benefits observed are retained long-term.

Introduction

Transcranial Direct-Current Stimulation (tDCS) is a non-invasive method of brain stimulation which can modify neuronal excitability through polarity-specific membrane potential alterations [1]. Regarding skilled motor function, tDCS can improve hand dexterity [2], motor sequence learning [3], and muscular endurance [4]. Therefore, it is conceivable that neurostimulation may be valuable to professions requiring high-level motor skills, such as surgery. However, to date, the benefits of tDCS on surgical skills acquisition are limited to studies in which the primary motor cortex (M1) or the supplementary motor area (SMA) were stimulated [5–8]. Importantly, considerable research has established the prefrontal cortex (PFC) as a key brain region for development of surgical skills, with greater PFC activation in novices and subsequent attenuation following development of expertise [9–17].

Achieving surgical proficiency is a highly topical issue since technical quality significantly impacts patient outcomes [18–20]. Reasons for discrepancy in technical skills are multifactorial and include new surgical techniques, increasingly technological complexity and reforms to surgical training. Technological innovations (e.g. robotic surgery, single-incision laparoscopic surgery), alongside new procedural complexity (e.g. pelvic exenteration), have limited trainee exposure to facilitate senior surgeon experience [21]. Furthermore, worldwide regulations on duty hours is manifest in limiting training opportunities [22,23] and reducing surgical experience [24]. Many surgical residents

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identify as being inadequately prepared for independent practice [25] and similarly, a substantial proportion are deemed incapable of operating independently by program directors [26].

Improving technical skills through neuromodulation with tDCS may accelerate time to proficiency and impact on patient safety. Ciechanski and colleagues [5–7] were the first to provide valuable evidence of tDCS in this context using a unilateral M1 montage and demonstrated improved neurosurgical resection metrics and pattern cutting scores, with the former being maintained over 6 weeks. Subsequently, Cox et al. [8] built on this with greater gains using multiple sessions of bilateral M1 stimulation over SMA stimulation. However, It is interesting to note certain methodological preferences (e.g. unilateral M1 stimulation, limited task familiarization and on-screen feedback) which may explain why in the neurosurgical resection task, no significant overall difference was detected between tDCS and sham groups in the amount of tumor resected, the amount of healthy brain resected or resection effectiveness [5]. Furthermore, although pattern-cutting scores were significantly higher with tDCS compared to sham after training, no significant differences were seen between stimulation groups across all time points in the peg-transfer task [6].

Given the role of the PFC in executive function, attention and motor learning [27,28], and previous neuroimaging findings in surgeons implicating the PFC in skills acquisition [9–17], we hypothesize that prefrontal stimulation might be a suitable target for performance enhancement in surgery, especially in the earliest "cognitive phase" of training [29]. Therefore, we investigated whether PFC-tDCS could improve the transient early phase of surgical skill development amongst novice surgeons towards proficiency.

Materials and methods

Participants

42 healthy medical students were recruited following Imperial College Research Ethics Committee approval (18IC4706). A sample size calculation was performed using an independent *t*-test based on the main effect of tDCS on surgical performance improvement in prior studies [5,6]. Specifically, detecting a 10% improvement in skill score with 85% power at a significance level of $\alpha = 0.05$, required a sample size of 36 participants. Written informed consent was obtained along with information on demographics, handedness and open knot-tying experience. A safety-screening questionnaire was administered [30,31] and participants were excluded if they had a history of traumatic head injury, neuropsychological condition, metallic implants, or adverse events to neurostimulation. Participants refrained from intake of stimulants including caffeine prior to the experiment and none were on regular medications. Those reporting prior knowledge of knot-tying were screened for pre-existing capabilities by requesting a demonstration of their knot-tying ability. Inclusion was dependent on agreement between two assessors (RP and JA) that no advantageous knot-tying skills were present – e.g. knowledge of initial hand positioning, finger/hand movements required, or techniques required to achieve a surgical reef knot. Accordingly, two participants were excluded due to task familiarity (see Data in brief).

Task training period

Participants were trained to perform surgical knot-tying on a commercial bench-based knot-tying trainer (Limbs & Things Ltd, Bristol, UK) in a 1-h session. They tied three 'reef' knots in a specific orientation, one on top of the other, using a single-handed technique. A description and video of this technique can be found at https://teachmesurgery.com/skills/surgical/knots. All but one of the participants were right-handed and all were taught the standard right-handed technique as it is common for surgeons to learn this procedure with both hands. To isolate task training, participants were trained in a laboratory setting free from distractors or additional personnel. To ensure uniformity, training was standardized, as previously described [9], with 50 min of structured guidance by the same instructor (JA) using a dual-colored cord. This stepwise approach entailed observation only, observation with direction, performance under direction, and finally stand-alone performance. Subsequently, participants had 10 min to acclimatize to 2-0 Polysorb Vicryl suture (Medtronic Ltd, Watford, UK). Throughout the training period, feedback was offered by the trainer to help improve performance to the required basic level of knot-tying ability. Feedback was withheld from the subsequent task evaluation period to limit confounding when evaluating the impact of tDCS.

Task evaluation period

Following training, participants were instructed to tie three-throws of a surgical reef knot to determine competency to proceed to task assessment. A double-blind randomized sham-controlled trial design was then employed (Fig. 1a). A randomization sequence was created using an online random number generator, stratified by gender, with a 1:1 allocation to either active or sham stimulation. They then completed three blocks of a knot-tying task pre-tDCS, online-tDCS and post-tDCS, each separated by a 10-min rest period. Participants were blinded to the mode of stimulation. Training and measurement of outcomes was restricted to one investigator (JA) who was blinded to group allocation and concealment was maintained until data collection was finalized.

Surgical task

Each block lasted 15 min during which nine repetitions of a surgical knot-tying task were performed with an identical number of knots placed during each block. For each repetition, participants tied a 46 cm 2-0 vicryl ligature around two parallel rubber cords, binding them together. Three knots were placed precisely over 5 mm colored segments (Fig. 2a), adapted from a validated proficiency-based knot-tying curriculum [32,33]. A maximum cutoff time of 60 s (s) was allowed for completion of each knot-tying repetition. This was followed by a 30s rest during which

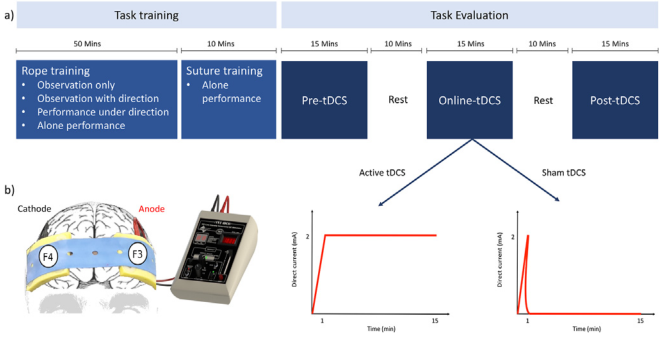

Fig. 1. a) Experimental design included 1 h of knot-tying training followed by three task blocks of open surgical reef knot-tying before, during and after "active" or "sham" stimulation. b) Soterix Platform 1X1 Low Intensity Smart ScanTM targeting the bilateral prefrontal cortex with the anode positioned over the left prefrontal cortex (F3 on the 10/20 electrode system) and cathode over the right prefrontal cortex (F4). Active stimulation delivered sustained 2 mA current for 15 min whilst sham stimulation delivered ramp up to 2 mA followed by an immediate ramp down. tDCS = transcranial direct-current stimulation.

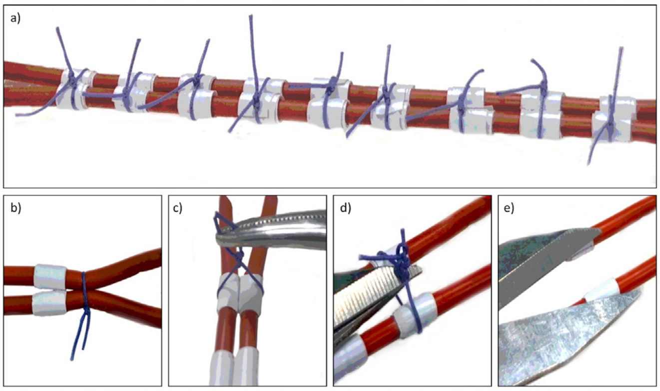

Fig. 2. - Surgical knot-tying task assessment. a
) Demonstration of nine knots completed by a participant within a single knot-tying task session. b
) Knot accuracy highlighted with arrow (mm). c
) Knot gap highlighted with arrow (mm) d) Knot slippage assessed using a spreader tool. e
) Complete slippage and unravelling of a knot demonstrated by the spreader tool.

participants were asked to relax, before recommencing the next knot-tying repetition. Participants were informed prior to the evaluation period that the speed, accuracy and security of their knots would be assessed, but were unaware of the scoring algorithm.

Transcranial direct-current stimulation

Stimulation was delivered using a Soterix 1X1 Low Intensity Smart Scan™ tDCS device (SOTERIX MEDICAL INC, New York, NY). A pair of 0.9% saline-soaked 35 cm^2 electrodes were placed over the bilateral prefrontal region and affixed by a single circumferential strap (Fig. 1b). For both active and sham stimulation, the anode was positioned over the left PFC and cathode over the right PFC (F3 and F4 in the 10/20 electrode system respectively) [34]. Increasing evidence suggests that 2 mA produces a net increase in excitability under the anode and cathode electrodes [35–37]. Accordingly, we selected this bilateral frontal montage at 2 mA to elicit a net increase in excitability in the prefrontal region and therefore, this montage was kept consistent for left and right-handed participants. Justification for montage selection is strengthened by prior studies demonstrating enhanced cognitive behavioral outcome measures [38–42] and increased inter-hemispheric connectivity following stimulation with bifrontal tDCS [43,44]. Fig. 3 illustrates a computational model [45] of expected current flow for the bifrontal montage utilized in this study. Both stimulation modes involved a 30-s ramp up to 2 mA. In the sham group this was followed by an immediate ramp down and remained at 0 mA for the remainder of the block (15 min). For active stimulation, after initial ramp up, current intensity was sustained at 2 mA for 15 min, followed by a 30-s ramp down.

Technical skill assessment

An adapted performance score (PS) based on a validated calculation [32,33] was determined by a single assessor (JA) blinded to group allocation, as follows:

PS (arbitrary units, au) = maximum cutoff time (60s) - [completion time - (10 x sum of errors)]

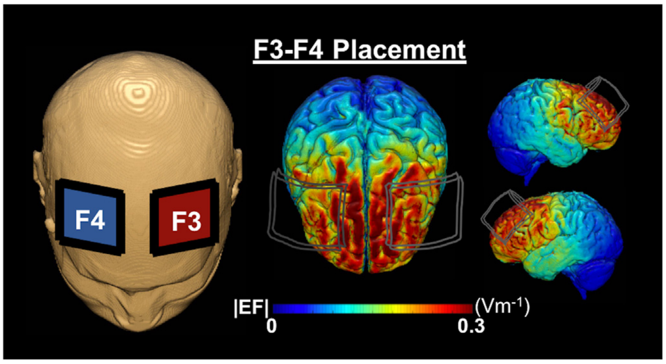

Fig. 3. – A computational model of electric field distribution for F3–F4 placement. The head model depicts the electrode arrangement with the anode (red) over F3 and cathode (blue) over F4. The brain models on the right depict the electric field strength and distribution which was calculated using a finite element-based approach in ROAST [45]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

The sum of errors (Fig. 2) was measured as follows:
Accuracy: distance (mm) that the suture was tied outside of the colored segments
Gap: distance (mm) between the suture knot and tubing segments
Slippage (au): 10 error points if the knot slipped >3 mm, 20 points if the knot unraveled
Breakage (au): 20 error points if the suture material fractured

Scott et al. [32] defined expert proficiency in this task as 50au. Although the original PS [32,33] assigned a score of zero to negative values, here we report the actual PS obtained by individuals. This modification was deemed necessary as our participants were naïve to the task, thus risking negative scores. Reporting actual scores enabled improved differentiation of performance as a result of the intervention.

Subjective workload and sensations

After each block, participants completed a SURG-TLX (Surgery Task Load Index) questionnaire [46] which is a validated, multi-faceted rating scale of subjective workload during a surgical task (full description provided in Data in brief). Participants were unable to view previous answers to avoid influence on subsequent scores. Following the online-tDCS block, all participants completed a four-point scale Visual Analogue Scale (VAS) questionnaire on side-effects requiring severity to be ranked from 0 (none) to 4 (strong) [47].

Data-analysis

Baseline demographics and estimation of intervention type were analyzed with chi-squared test. All outcomes measures were observed to be non-parametric following testing of normality using the Shapiro-Wilk test. For technical performance assessment, PS and its subcomponents (time and error) were analyzed; subcomponent analysis allowed a meaningful understanding of changes in PS and whether it reflected overall performance change rather than, for example, an isolated quicker performance. Performance was analyzed using a generalized linear mixed model (GLMM) for interaction and main effects of group and block, with participant as a random effect. Data was transformed by subtracting individual PS from the highest PS value in the dataset to meet the requirements of a Gamma distribution. Models were compared using the Akaike information criterion (AIC) with the smallest AIC retained. Tukey's post-hoc test was used to correct for multiple pairwise comparisons. To corroborate the GLMM, Friedman's test was used to analyze change across blocks and the Mann-Whitney *U* test to identify differences between the intervention groups (reported in Data in brief).

Further analyses stratified participants into 'low-skill' and 'high-skill' subgroups categorized by pre-tDCS performance ('low-skill' = bottom 50% of scores; 'high-skill' = top 50% of scores). To test change in subgroup PS and overall SURG-TLX scores over the three blocks, the Friedman's test was used. The Wilcoxon signed-rank test with Bonferroni correction was used for post-hoc comparisons. For comparison of subgroup PS and overall SURG-TLX scores between the intervention groups at each block, the Mann-Whitney *U* test was used. Additionally, to elucidate variation within task blocks, a comparison of the first four and last four knots in each block was performed using the Wilcoxon signed-rank test. To compare proportions and severity rankings of sensations between the intervention groups, Fisher's exact test and independent *t*-test were employed. A p-value <0.05 was considered statistically significant. Analysis was performed using the lme4 package in R v.3.6.3 (The R Foundation for Statistical Computing, Vienna) and SPSS v.25.0 (IBM Corp, Armonk, NY).

Results

Following training, all 40 participants successfully completed three throws of a surgical reef knot to demonstrate sufficient competency to proceed to task assessment. There were no significant demographic differences between the two groups (Table 1).

Knot-tying task performance

There was no pre-tDCS difference in knot-tying PS between active and sham groups [median (IQR) PS: active pre-tDCS −1.0au (19.25) vs. sham pre-tDCS −1.0au (34.25); $p = 0.87$], suggesting that the task training period was comparable for both groups.

The interaction between intervention and block was a predictor for PS ($t = 4.987$, $p < 0.001$). As illustrated in Fig. 4 and highlighted in Table 2, PS improved with active tDCS over the three blocks (pre- vs. online/post-tDCS, $p < 0.001$). Conversely, a non-significant deterioration in PS over the three blocks was observed in the sham group. PS was significantly higher following active tDCS compared to sham ($p = 0.002$). No significant differences were observed between the active and sham groups in the pre- and online-tDCS blocks.

Secondary analyses (reported in Data in brief) is illustrated in Fig. 5a and indicates greater PS improvement in the active group from pre-to post-tDCS in both 'low-' ($P = 0.005$) and 'high-skilled' participants. Improvement with sham stimulation was more marginal for the subgroups. PS was significantly higher following active stimulation in both 'low-' ($p = 0.02$) and 'high-skilled' ($p = 0.03$) subgroups compared to sham. Most participants in the active

Table 1
Group demographics.

	Active (n = 20)	Sham (n = 20)	p-value
Participant Demographics			
Mean age in years (SD)	21.30 (2.47)	21.85 (2.18)	0.37
Mean year of study (SD)	2.55 (2.26)	1.95 (1.93)	0.21
Male (%)	9 (45)	9 (45)	1.00
Female (%)	11 (55)	11 (55)	
Handedness, n (%)			
Right	19 (95)	19 (95)	1.00
Left	1 (5)	1 (5)	

Fig. 4. – Individual performance scores across the three blocks for active and sham groups. Bold lines represent median group performance score. Outliers removed to aid graphical representation.

Table 2
– Performance and workload outcome measures. Values are medians.

	Active (n = 20)	Sham (n = 20)	p-value
Performance Outcome Measures			
Performance Score (au)			
Pre	- 1.0	- 1.0	0.87
Online	5.5 ***	- 6.5	0.16
Post	16.0 ***	- 18.5	<0.01
Time (s)			
Pre	45.5	46.0	0.76
Online	44.0 ***	42.0 **	0.90
Post	38.5 ***	37.0 ***	0.74
Error (au)			
Pre	1.5	2.0	0.90
Online	1.0 ***	2.0	0.09
Post	0.0 ***	3.0	<0.001
SURG-TLX			
Mental Demand			
Pre	26.0	23.0	0.57
Online	26.0	18.0	0.53
Post	18.0	29.0	0.80
Physical Demand			
Pre	15.5	8.5	0.18
Online	19.0	13.5	0.30
Post	20.5	9.5	0.43
Temporal Demand			
Pre	37.5	24.0	0.34
Online	11.0 **	20.5	0.51
Post	8.0 **	15.0	0.29
Task Complexity			
Pre	23.0	32.5	0.30
Online	20.5	24.0	0.46
Post	13.5	21.0	0.17
Situational Stress			
Pre	43.0	50.0	0.97
Online	20.0 *	14.0 **	0.45
Post	11.0 ***	13.5 ***	0.55
Distractions			
Pre	0.0	0.0	0.82
Online	1.0	0.0	0.72
Post	0.0	0.0	0.86

Asterisk indicates significant difference from the 'pre-' block in post-hoc testing. * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.

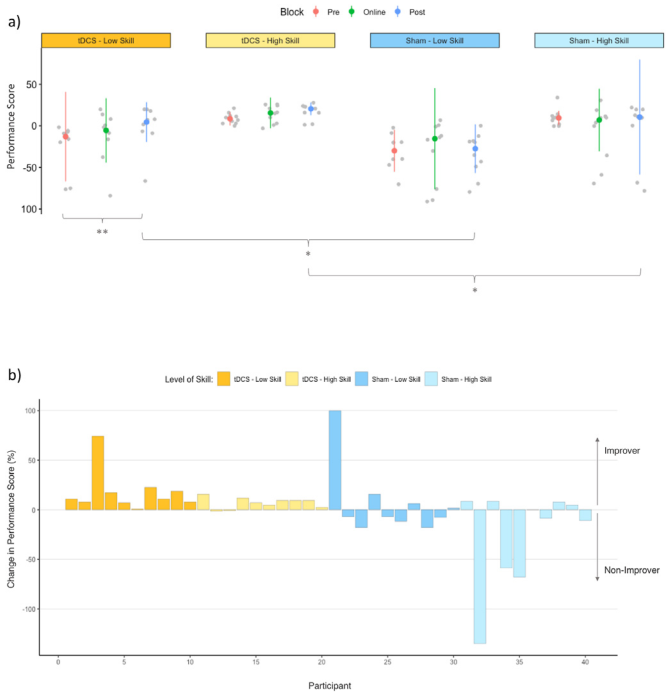

Fig. 5. – Performance change in low and high-skill subgroups. a) Scatter plot of individual performance score within each subgroup (represented by grey dots). Colored dots and line represent subgroup median performance score and inter-quartile range. Outliers removed to aid graphical representation. Asterix denotes significant difference, * = p < 0.05, ** = p < 0.01. b) Change in performance score from pre-to post-as a percentage of the highest improver – divided into subgroups.

subgroups improved, whilst a more variable response was identified in the sham subgroups (Fig. 5b). No demographical differences were identified between improvers and non-improvers in the sham group. Analysis within each block generally revealed PS improvement in the last four knots compared to the initial four knots with only the online sham block observing deterioration as the block progressed ($p = 0.04$).

Error and time

The improvement in PS in the active group appeared to be driven by a reduction in error score, specifically knot accuracy. The interaction between intervention and block predicted for error ($t = 4.647$, $p < 0.001$), with significant improvement over the three test blocks (pre-vs. online/post-tDCS, $p < 0.001$). A non-significant increase in error score was observed in the sham group over the three blocks. Error score following active stimulation was significantly lower compared to sham ($p < 0.001$). No other differences in error scores were observed between the two groups. A main effect of block was observed for the time-taken to complete the task ($t = 3.965$, $p < 0.001$). A significant reduction in time was observed over the three blocks in both active (pre-tDCS vs. online/post-tDCS, $p < 0.001$) and sham groups (pre-tDCS vs. online-tDCS, $p = 0.002$; pre-tDCS vs. post-tDCS, $p < 0.001$]. There was no difference between the active and sham groups in the median time taken for knot completion in any block.

SURG TLX workload

Significant differences across the three task blocks were observed in temporal demand [$\chi^2(2) = 15.707$; $p < 0.001$] and situational stress [$\chi^2(2) = 16.730$; $p < 0.001$] in the active group. Post-hoc analysis demonstrated significant reductions from pre to online blocks and from pre to post blocks in both temporal demand and situational stress (Table 2). In the sham group, only situational stress changed significantly across blocks [$\chi^2(2) = 25.289$; $p < 0.001$], and post-hoc analysis revealed significant reductions from pre to online and from pre to post (Table 2). For the remaining subjective workload domains, there were no significant differences between the two groups or across blocks for either group.

Sensations and side effects

Sensation reports are provided in Data in brief. Overall, there was no significant difference in sensations between groups, and there were no serious adverse events. Less than half (47.5%, $n = 19$) of participants felt that tDCS had a 'mild' impact upon their performance and no stronger impact felt. A greater number in the active ($n = 14$) compared to the sham ($n = 9$) group guessed that they received active stimulation. Only four participants correctly guessed their stimulation mode in the sham group. There was no statistical difference in distinguishing between active and sham stimulation (χ^2 $(2) = 3.220$, $p = 0.20$), suggesting validity of blinding with the sham protocol.

Discussion

This double-blind randomized controlled trial identified statistically significant improvements in early-phase knot-tying technical performance with prefrontal tDCS, regardless of whether novices were 'low-' or 'high-skilled' from the outset, and with a clear propensity to improve participants compared to sham. Furthermore, we demonstrate, for the first time, a reduction in temporal demands associated with surgical task execution using tDCS.

We targeted the PFC due to the considerable evidence demonstrating a distinct associative network, including the dorsolateral PFC, contributing to early motor performance [27–29]. The PFC facilitates reaction to sensory inputs, movement and sequence planning, and performance calibration through attention to action. As performance is repeated, PFC activation declines and sensorimotor networks become more prominent in later stages of motor learning [9,13,17]. Technical skill improvement with PFC stimulation is theorized to be secondary to augmented PFC efficiency. To direct stimulation towards the PFC, we utilized a F3/F4 montage using conventional tDCS, which is thought to provide a broad stimulation pattern to the entire frontal lobes. Stimulation with 1 mA has commonly shown increased excitability under the anode and a decrease under the cathode. However, current intensity plays a critical role in the pattern of excitability with research demonstrating that 2 mA stimulation delivers a net increase in excitability under both anodal and cathodal electrodes [35–37]. A bifrontal montage at 2 mA has not only demonstrated improved cognitive behavioral measures, including working memory, task switching and inhibitory control [38,39,43,44], but has also recently facilitated functional connectivity in left frontal cortices – even with the cathode placed over left PFC [43,44]. These data, in addition to work by Nitsche and colleagues demonstrating net excitatory effects from 2 mA stimulation [35,36], provide a strong basis for selection of the current montage.

A common misconception, fostered by historical localizationism in brain sciences, is that focal stimulation is "better." However, as we increase our understanding of cortical pathways as complex and interconnected networks, stimulation of multiple nodes within a network may prove beneficial, versus stimulation of a single node – especially when the exact node central to improvement is relatively unknown. Parra and colleagues have recently demonstrated that tDCS effects follow the principle of Hebbian plasticity [48]. That is to say that: *“neurons that fire together, wire together”*. Previous research demonstrated that pairing a cognitive task with tDCS is more effective than stimulation prior to the task [49]. Thus, tDCS effects appear to involve the interaction between delivered electric current altering the resting membrane potential of tissue and activation of the target brain system through behavioral task engagement. While stimulation from conventional tDCS is broad in patterns, effects are likely related to the “co-stimulated” systems engaged by stimulation. Consistent with these findings, we designed a study that delivered tDCS during task performance and stimulated a broad area of tissue in the frontal cortices that are theoretically important for task performance.

Although valid concerns exist regarding shunting of electrical current with electrodes in close proximity [50], all tDCS is considered to involve a degree of shunting of current through the skin. Bifrontal stimulation has been a commonly applied montage across cognitive applications in tDCS [51–53] and our computational model (Fig. 3) demonstrates a maximal electrical field strength of 0.3 V/m, which is consistent with conventional tDCS applications. In older adults, with brain atrophy, electrical field strengths of only up to 0.2 V/m are typically observed yet continue to demonstrate working memory improvements [44]. This is in keeping with the central premise of tDCS that a large amount of current is not required to penetrate tissue to provide a small, but meaningful change in the resting membrane potential of neurons [54].

Over the three blocks, sham learners were observed to have greater variability with a marginal decline in median PS across the blocks. As the current study involved only 2 h of knot-tying, the amount of practical exposure may not have been sufficient to deliver improvements under sham conditions. Furthermore, performance could have been adversely affected by mental and physical demands as supported in SURG-TLX data (Table 2). Inattention and fatigue could prompt performance deterioration, as observed in previous studies [55,56]. Furthermore, recent studies suggest excessive demands have produced poor and even deactivation responses in the PFC associated with detriment to technical performance [57]. Conceivably, active tDCS may augment PFC neuronal efficiency to offset these demands (Table 2), maintain attention and concentration, and improve technical performance.

Aside from targeting the PFC, we aimed to methodologically extend previous tDCS studies in the surgical setting. Firstly, whilst trainees have previously received on-screen feedback [5], we sought to ensure that participants were free from guidance and feedback during the task itself, thus better isolating the impact of tDCS. Compared to the hour of training here, prior studies [5–8] had limited task training prior to tDCS sessions, and it is conceivable that participants were still familiarizing themselves to the task during tDCS episodes. We aimed to carefully evaluate and control for prior task exposure, whereas others had a propensity towards more senior students receiving active stimulation [6] and use of participants not affiliated with medicine [8].

In terms of clinical relevance, previously, ‘low-skill’ trainees often benefitted more from tDCS [5]. Here, significant improvement in both ‘low-’ and ‘high-skilled’ participants with tDCS compared to sham suggests PFC stimulation may be beneficial to trainees in early learning. The present study employs a basic and fundamental task employed throughout numerous aspects of medicine and surgery, applied to an appropriate target population. Although no participants achieved proficiency level, likely due to the relatively short exposure within this study, participants were closer to proficiency following active tDCS compared to sham. The knot-tying task used here may have more real-world potential given that the exact knots tied here are used throughout surgical practice. Since poor knot quality can result in technical failures such as wound dehiscence [58,59], the importance in achieving proficiency in knot-tying skill is widely accepted, extensively researched, and intrinsic to patient safety [32,33,60–62]. Furthermore, this study demonstrates a reduction in subjective temporal demand which could align with previous evidence of a bifrontal montage alleviating physiological parameters of stress [63]. This finding is interesting given that stress impairs surgical performance [64] and recent research suggests that surgeons who can sustain PFC activation(s) under stressful conditions are able to maintain performance within certain limits despite these demands [57]. Therefore, the potential for tDCS to reduce subjective stress in the operating theatre could lead to a reduction in technical errors and have potential for improved patient outcomes.

Safety

Whilst well-known to the neuroscience community, it is important to emphasize safety aspects of tDCS to surgical readers. An extensive review [31] on tDCS safety found no serious adverse events documented in 33,200 sessions in 1000 participants. Common minor side effects include “tingling”, “itching” and “redness”, which are transient and subside following stimulation. Nitsche et al. [65] revealed no changes in neuron-specific enolase, a protein associated with neuronal death, in participants undergoing tDCS. Additionally, MRI scans found no evidence of brain edema, disturbance of the blood-brain barrier or structural brain alterations following tDCS [66]. Despite this, it is important to highlight that long-term safety outcomes from single and repeated tDCS exposure remain unknown. While unlikely that serious adverse events will unexpectedly occur downstream, it is important that long-term safety studies be conducted prior to tDCS use in routine surgical practice.

Limitations

Only single session tDCS in the initial stage of surgical skill development was evaluated. Multiple tDCS sessions would more accurately replicate surgical training and facilitate learning curve assessments. Furthermore, without retention testing, we are unable to confirm evidence of tDCS-induced motor learning. Finally, participants were medical students, and not attending surgeons or residents. However, the aim was to investigate the earliest phases of surgical skill development, hence the population and the fidelity of the task under investigation were deemed appropriate. Alongside multiple sessions with retention testing, future work would benefit from neuroimaging techniques alongside a comparison of associative vs. sensorimotor cortex electrode locations. This would further understanding of neurophysiological mechanisms and guide towards the most efficacious tDCS assembly in surgeons. A key additional area of exploration is to investigate benefits of tDCS over and above the gains expected with conventional educational adjuncts and feedback.

Conclusions

This study suggests that tDCS improves transient gains in technical surgical skills acquisition. The application of tDCS in the context of surgical training appears safe in the short-term but further studies are required to confirm long term motor learning efficacy and safety.

Meeting presentations

- RCS Innovation in Surgical Education, June 2019. London, UK.
- Non-Invasive Brain Stimulation, March 2020. Baden Baden, Germany.

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CRediT authorship contribution statement

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Declaration of competing interest

The authors declare no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.brs.2020.10.013.

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