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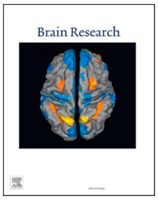

The effects of unilateral transcranial direct current stimulation on unimanual laparoscopic peg-transfer task

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ABSTRACT

Introduction: Efficient training methods are required for laparoscopic surgical skills training to reduce the time needed for proficiency. Transcranial direct current stimulation (tDCS) is widely used to enhance motor skill acquisition and can be used to supplement the training of laparoscopic surgical skill acquisition. The aim of this study was to investigate the effect of anodal tDCS over the primary motor cortex (M1) on the performance of a unimanual variant of the laparoscopic peg-transfer task.

Methods: Fifteen healthy subjects participated in this randomized, double-blinded crossover study involving an anodal tDCS and a sham tDCS intervention separated by 48 h. On each intervention day, subjects performed a unimanual variant of laparoscopic peg-transfer task in three sessions (baseline, tDCS, post-tDCS). The tDCS session consisted of 10 min of offline tDCS followed by 10 min of online tDCS. The scores based on the task completion time and the number of errors in each session were used as a primary outcome measure. A linear mixed-effects model was used for the analysis.

Results: We found that the scores increased over sessions ($p < 0.01$). However, we found no effects of stimulation (anodal tDCS vs. sham tDCS) and no interaction of stimulation and sessions.

Conclusion: This study suggests that irrespective of the type of current stimulation (anodal and sham) over M1, there was an improvement in the performance of the unimanual peg-transfer task, implying that there was motor learning over time. The results would be useful in designing efficient training paradigms and further investigating the effects of tDCS on laparoscopic peg-transfer tasks.

1. Introduction

Laparoscopic surgery is a minimally invasive method of surgery with advantages over conventional techniques, including a reduction in blood loss, post-operative pain, and incision scars (Klempous et al., 2018). Since laparoscopic tools are inserted through a small cavity, surgeons have reduced or altered tactile-sensation, limited degrees of freedom of movement, and indirect vision during a laparoscopic procedure (Gallagher and O'Sullivan, 2012; Spruit et al., 2016). With the increase in demand for minimally invasive surgical procedures, the requirement for associated technical skills (Spruit et al., 2016) and appropriate training procedures have also increased.

The set of processes encompassing skill acquisition and motor adaptation brings about a relatively permanent change in a person's behavior and is known as motor learning (Nieuwboer et al., 2009; Schmidt et al., 2018). The principles of motor learning are also applicable to learning laparoscopic skills (Spruit et al., 2016). Numerous methods are available for learning laparoscopic skills, such as training using animal models, simple box trainers, and virtual reality (VR) based trainers (Palter et al., 2010). Simple laparoscopic trainers are preferable in terms of cost-effectiveness (Nguyen et al., 2013). Laparoscopic training tasks include peg- or bead-transfer, pattern cutting, intra-, and

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extra-corporeal knots, placement of a mesh over a defect, placement of a ligating loop, and placement of a clip at appropriate positions (Derossis et al., 1998).

Many studies have shown that motor learning can be enhanced by increasing cortical excitability (Boggio et al., 2006; Nitsche et al., 2003b; Stagg et al., 2011). One of the commonly used methods for modulating neural plasticity is transcranial direct stimulation (tDCS) (Paulus, 2011). tDCS is a non-invasive brain stimulation technique for modulating motor cortex excitability by applying small amounts of direct current on a person's scalp (Nitsche and Paulus, 2000). The current is applied using two or more electrodes depending upon the configuration; however, a simple bipolar configuration is composed of two electrodes called anode and cathode. Current travels through the anode into the brain tissue and returns to the cathode, stimulating the underlying cortical neurons (Philip et al., 2019). However, both anode and cathode can be used for active stimulation and the electrode at the stimulation site is usually termed as an active electrode (Galletta et al., 2015). Although some current is lost at scalp, a substantial amount of current penetrates the brain to modify the excitability levels of underlying neurons (Bolognini et al., 2011; Nitsche et al., 2003a; Zaghi et al., 2010). These effects are reversible and can usually last up to an hour or more after stimulation and are dependent upon the duration of stimulation (Nitsche and Paulus, 2001). In terms of mechanism of action, tDCS mediates the transmembrane potentials of cortical neurons and does not act by inducing the action potentials (Bolognini et al., 2011). The modulation of sodium and calcium gated channels and N-methyl-D-aspartate (NMDA) receptor activity produces effects similar to long-term potentiation (LTP) and long-term depression (LTD), that are associated with neuronal plasticity (Liebetanz et al., 2002; Nitsche et al., 2004).

Since anodal tDCS enhances cortical excitability, it is assumed that it may also improve motor learning by enhancing neuroplasticity (Reis and Fritsch, 2011). For example, anodal tDCS over the primary motor cortex (M1) has been found to improve motor learning in implicit (Nitsche et al., 2003b) and explicit motor learning tasks (Stagg et al., 2011), visuomotor task performance (Antal et al., 2004), and performance of non-dominant hand in hand function test (Boggio et al., 2006). However, the effect of tDCS over the primary motor cortex (M1) could also be task-specific since no improvement has also been reported on bimanual motor task (Vancleef et al., 2016). Despite the reports showing tDCS over M1 has no impact on motor performance, numerous studies have shown positive influence of tDCS on motor task performance (for review (Buch et al., 2017)).

Recently, there has been some interest in the application of tDCS for the enhancement of laparoscopic skill acquisition. When we started this study (March 2018), only one study (Ciechanski et al., 2018) looked at the effects of tDCS on laparoscopic training and found no significant effect of tDCS on the peg-transfer task; however, a significant improvement for the pattern-cutting task was observed. Despite no significant improvement in the peg-transfer task, an appropriately powered study could detect a medium effect size as found in (Ciechanski et al., 2018). Moreover, the commonly used peg-transfer task is bimanual; thus, it is expected that the application of anodal tDCS on the dominant side alone may not improve the performance of a bimanual task (Ciechanski et al., 2018; Vancleef et al., 2016). Two recent studies (Ciechanski et al., 2019; Cox et al., 2020) have also reported no impact of anodal tDCS over M1 compared to sham for laparoscopic peg-transfer task.

Since none of the studies reported positive impact of anodal tDCS on laparoscopic peg-transfer task, it is possible that the non-significant findings in previous studies (Ciechanski et al., 2018; Ciechanski et al., 2019) are due to the disparity of using stimulation of dominant hemisphere only, while the task being a bimanual task. A later study (Ciechanski et al., 2019) suggested that anodal tDCS might only be useful for unimanual tasks (such as pattern-cutting) and not for bimanual laparoscopic tasks (such as laparoscopic peg-transfer task). We thus modified the bimanual laparoscopic peg-transfer task into a unimanual laparoscopic peg-transfer task and conducted this double-blinded randomized crossover study to evaluate if anodal tDCS over M1 of the dominant hemisphere can affect *unimanual* variant of the laparoscopic peg-transfer task. We hypothesized that anodal tDCS over M1 would improve the performance of the unimanual laparoscopic peg-transfer task.

2. Results

One of the 16 subjects was uncomfortable with the tDCS, and thus, the stimulation session was discontinued after 10 min (pre-task). We excluded the subject from the analysis, and results from 15 subjects are reported here. All 15 subjects filled a questionnaire after completing the experiment regarding tDCS tolerability and blinding. Due to loss of data, tolerability information from 9 subjects is reported here. 8/9 subjects reported itching (4 mild; 4 moderate), 3/9 reported mild sensation of numbness, 3/9 reported sensation of pain (2 mild; 1 moderate), 3/9 reported headache (1 mild; 2 moderate), 4/9 reported discomfort (2 mild; 2 moderate), and 4/9 reported burning sensation (2 mild; 2 moderate). 3 of the 9 subjects correctly guessed the order of active and sham stimulation sessions.

The scores of subjects from all sessions are presented in Fig. 1. Although there seems to be a slight difference in the subjects' mean scores in both stimulation types, the variance was relatively high.

The main effects of the factors "Stimulation" and "Session" and their interaction are provided in Table 1. We found no significant interaction of factors "Stimulation" and "Session" ($F(2, 55.40) = 0.19$, $p = 0.83$), and no main effect of "Stimulation" ($F(1, 19.03) = 0.03$, $p = 0.856$). A significant effect of "Session" was observed ($F(2, 58.22) = 7.76$, $p = 0.001$). The significant effect of "Session" showed that the performance of subjects improved over time, and there was no difference in their scores because of the type of Stimulation.

Estimated marginal means of the main effects of Stimulation and Session and interaction of Stimulation and Session are presented in Tables 2–4 respectively.

The post hoc analysis of the factor "Session" (Table 5) revealed significant improvement of scores from Session 1 to Session 2 (mean difference (Session 2 – Session 1) = 57.33, $p < 0.01$), and from Session 1 to Session 3 (mean difference (Session 3 – Session 1) = 63.02, $p < 0.01$) but the improvement in scores was not significant from Session 2 to Session 3 (mean difference (Session 3 – Session 2) = 5.69, $p > 0.05$).

The results from repeated measures ANOVA (Table S1) and bayesian repeated measures ANOVA (Table S3) are provided in supplementary file and are similar to the results reported here using linear mixed model analysis. Repeated measures ANOVA showed no significant differences for the factor Stimulation and only a significant effect of the factor Session (Table S1) whereas bayesian repeated measures ANOVA only showed strong evidence for an effect of the factor Session (Table S3).

3. Discussion

This study presents the effects of anodal tDCS over the M1 region on the unimanual variant of the laparoscopic peg-transfer task. We used a modified laparoscopic peg-transfer task to test unimanual performance enhancement. Our results show that there was an improvement in performance over sessions. However, this was not related to tDCS as a single session of anodal tDCS over the M1 region did not affect the laparoscopic peg-transfer task compared to sham stimulation.

It has been reported previously that unilateral tDCS does not affect the bimanual peg-transfer task (Ciechanski et al., 2018; Ciechanski et al., 2019) while bilateral tDCS only has an online effect on the bimanual peg-transfer task (Cox et al., 2020). It has been suggested previously that unimanual laparoscopic tasks (such as laparoscopic pattern-cutting) may be more sensitive to modulatory effects of tDCS (Ciechanski et al., 2019). Since previously used laparoscopic peg-transfer task is a bimanual task (Ciechanski et al., 2018, 2019; Cox et al., 2020), we thus

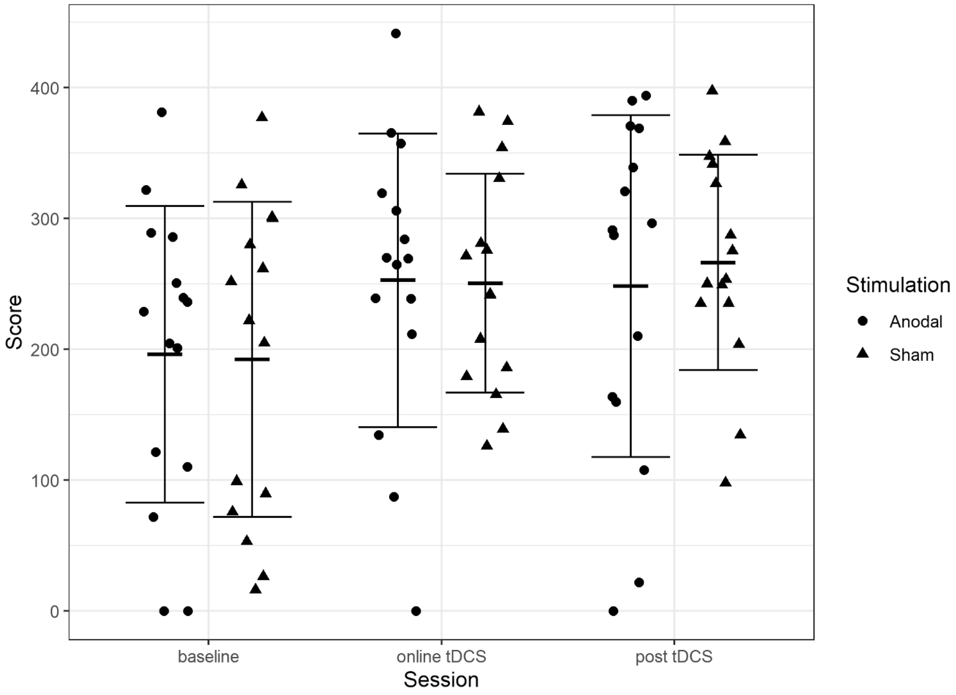

Fig. 1. Scores. Circles and triangles show individual scores. Error bars show mean ± SD scores.

Table 1
Type III Tests of Fixed Effects.

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	14.44	127.53	0.000
Stimulation	1	19.03	0.03	0.856
Session	2	58.22	7.76	**0.001**
Stimulation * Session	2	55.40	0.19	0.830

Table 2
Estimated marginal means of the factor Stimulation.

Stimulation	Mean	Std. Error	df	95% Confidence Interval
Active	232.44	23.41	22.54	[183.95, 280.93]
Sham	236.43	23.41	22.54	[187.94, 284.92]

Table 3
Estimated marginal means of the factor Session.

Session	Mean	Std. Error	df	95% Confidence Interval
Baseline	194.32	22.96	21.29	[146.62, 242.02]
Online tDCS	251.65	22.96	21.29	[203.95, 299.25]
Post tDCS	257.34	22.96	21.29	[209.64, 305.04]

Table 4
Estimated marginal means of the interaction Stimulation and Session.

Stimulation	Session	Mean Score	Std. Error	df	95% Confidence Interval
Active	Baseline	196.27	27.65	39.59	[140.38, 252.16]
	Online tDCS	252.67	27.65	39.59	[196.87, 308.66]
	Post tDCS	248.27	27.65	39.59	[192.38, 304.17]
Sham	Baseline	183.446	27.65	39.59	[136.47, 248.26]
	Online tDCS	246.235	27.65	39.59	[194.64, 306.43]
	Post tDCS	269.225	27.65	39.59	[210.51, 322.29]

Table 5
Post hoc analysis of the factor Session.

Comparison		Mean Difference	Std. Error	df	Sig.	95% Confidence Interval
Session 1	Session 2	−57.33*	16.24	57.31	**0.002**	[−97.37, −17.29]
Session 1	Session 3	−63.02*	18.35	67.79	**0.003**	[−108.06, −17.98]
Session 2	Session 3	−5.69	16.24	57.31	1.000	[−45.73, 34.35]

modified the bimanual peg-transfer task to a unimanual variant to assess whether unilateral tDCS M1 stimulation during unimanual laparoscopic peg-transfer task improves performance as suggested in (Ciechanski et al., 2019). Contrary to our hypothesis, we found no effect of stimulation, neither on online learning or offline learning, and thus were unable to replicate the results of the study by Cox et al. (2020). However, similar to (Cox et al., 2020) we found no active vs sham difference from pre-test to post-test performance and thus our hypothesis was rejected. The absence of online learning could be because we only gave stimulation in a single training session compared to other studies, which provided stimulation across multiple training sessions and possibly minimized learning over time (Ciechanski et al., 2018; Ciechanski et al., 2019; Cox et al., 2020). We also found no interaction effect of stimulation-type and sessions, which means that there was no post-stimulation difference in scores between active and sham stimulations. Our results suggest that unilateral tDCS may not have a significant effect on the unimanual peg-transfer task, and the modulatory effect of tDCS could only be task specific and not because of unimanual task practice as suggested in (Ciechanski et al., 2019).

Although no statistically significant effects were observed for tDCS on the peg-transfer task, the discussion on effect size may provide some further explanation. Our study design was powered to detect an effect size of 0.4 with the power of 90%. This was based on post-test statistical differences reported in (Ciechanski et al., 2018) which had an effect size of Hedge's g = 0.40. In our study, the effect sizes for Stimulation (η_p^2 =

0.001) and interaction of Stimulation and Session ($\eta_p^2 = 0.03$) are close to zero (Table S1). Moreover, Bayes Factor (BF) from the bayesian analysis (Table S3) suggested that there is a 4.54 times more evidence for null hypothesis (null effect) than our alternate hypothesis for the factor "Stimulation" ($BF_{10} = 0.22$), which is considered moderate evidence (van Doorn et al., 2020). Since we could not detect the a priori effect size with an appropriately powered study, this could mean that the actual effect size is much lower than the estimated effect size. It is likely that sample size estimation based on post-test statistical differences from (Ciechanski et al., 2018) resulted in reduced power than intended. However, later two studies also found medium effect sizes but the effect sizes were negative (Hedge's $g = -0.44$ (Ciechanski et al., 2019), Glass's $\Delta = -0.56$ (Cox et al., 2020)). These effect sizes, however, are likely to be more conservative as they are calculated from the reported data and do not account for the correlations between repeated measures (equations used for calculation of effect sizes of each study are provided in the supplementary file). Two studies (Ciechanski et al., 2018; Ciechanski et al., 2019) did not report effect sizes, and one study (Cox et al., 2020) had three groups and thus effect size of anodal M1 vs sham comparison was not available. Thus, due to inconsistent effect size reports, it is not yet clear whether tDCS improves the performance of the peg-transfer task, deteriorates it, or has no impact; therefore, further investigation is required to avoid using intervention with negative effects.

The peg-transfer task used in this study was modified for two reasons. One reason was to digitally measure the task timings instead of using commonly used video recordings. The second was to test for the possibility of unimanual performance enhancement. Moreover, the task we designed was relatively difficult than the standard peg-transfer task described in (Derossis et al., 1998). The original peg-transfer task (detailed in Section 6.4 Peg-Transfer Task) is a bimanual task that requires the transfer of objects from left pegs to right pegs on board and then from right to left. The objects to be transferred are larger and easier to carry or move. Thus, it would be suitable to use alternatives with different complexity levels of the task to allow further improvement and not limit performance. Yet, our task showed a main effect of sessions, which means that subjects' performance improved over three sessions since significant improvement from Session 1 to Session 2, and Session 1 to Session 3 was observed despite the difficulty of the task. However, the improvement from Session 2 to Session 3 was not significant suggesting slowing down of learning after two practice sessions.

In terms of study design, there is evidence that motor performance can be enhanced by a single session of tDCS (Antal et al., 2004; Boggio et al., 2006; Nitsche et al., 2003b). However, multi-session tDCS spanned across multiple days has been found to have much larger performance enhancements in motor skill acquisition, which is mainly attributed to the consolidation effect and not within-session learning (Reis et al., 2009). This superiority of performance can last up to months as well (Reis et al., 2009). Our study could not find an effect on performance with a single session of tDCS. Since there is a main effect of sessions, it could mean that learning is too plastic and has a large margin of improvement over sessions. Thus, it would be difficult to single out the effect of the intervention in a single session in such a scenario. The difference, if any, would be much clear if evaluated at asymptotic learning levels. Our study suggests that after two practice sessions, learning starts to slow down as we did not find significant differences between the scores of Session 2 and Session 3.

Only one study has previously used slightly similar experiment protocol (Stagg et al., 2011). Stimulation started 10 s before the task and continued for 5 min after the task in one of the experiments (Stagg et al., 2011). The authors found a deteriorating impact of this protocol on task performance. Stimulation in our study started 10 min before the task and ended with the task approximately (since subjects can vary slightly in their time of task completion). However, a recent study reported no difference in performance of a motor task during either online or offline tDCS over sensorimotor cortex (Besson et al., 2019). Nonetheless, there is evidence of positive impact of both type of stimulations on motor task performance (for review (Buch et al., 2017)). There is also evidence to suggest that online tDCS improves online performance (Kantak et al., 2012; Karok and Witney, 2013; Sriraman et al., 2014) whereas offline tDCS (pre-task stimulation) is considered to improve offline learning or early consolidation (Antal et al., 2008; Convento et al., 2014; Krause et al., 2016). The evaluation of this combined method (combined use of offline + online tDCS) was not the purpose of this study; however, based on the previous studies, we expected a positive impact on the online task performance as well as early consolidation (in post-tDCS session) by using the combination of offline- and online-tDCS. Moreover, it is unclear whether offline tDCS application had any kind of deteriorating effect in our study as previously reported in (Amadi et al., 2015; Stagg et al., 2011), since the variance of scores is quite high in our data and there is not much difference in mean scores.

Despite the positive findings, contradictory findings have also been reported in literature. Some studies have reported a deteriorating impact of anodal tDCS applied over M1 on the motor task performance (Amadi et al., 2015; Stagg et al., 2011). Furthermore, there are also some studies (for review (Horvath et al., 2014)) suggesting that online stimulation (stimulation with concurrent task practice) can reduce or even eliminate the efficacy of stimulation, which could be one reason that we were unable to see any impact of stimulation in our study. While there are less reports of deterioration of task performance, considerable reports exist showing anodal tDCS over M1 has no impact on task performance (Ambrus et al., 2016; Kuo et al., 2008; Lindenberg et al., 2013; Soekadar et al., 2014; Vancleef et al., 2016). Considering the inconsistencies in previous reports, more focus on interaction between tDCS induced cortical excitability and the task performance is required, as there are previous reports suggesting that learning can be predicted by motor cortex excitability (Antal et al., 2007; Bortoletto et al., 2015; Miyaguchi et al., 2013; Quartarone et al., 2004).

4. Limitations

This study has some limitations. Considering that this is one of the earlier studies evaluating the effect of tDCS on laparoscopic peg-transfer task and the first study to use a unimanual peg-transfer task, the sample size estimates might not be accurate. We powered our study based on effect size from (Ciechanski et al., 2018) but failed to detect any difference in the intervention. This means a much bigger sample size is required to get an accurate estimate of true effect size.

The modified peg-transfer task that we used is relatively different from the simpler versions available, considering that it was designed to accommodate the digital nature of the laparoscopic trainer. This reduces the equivalence of comparison of raw scores between studies; however, standardized comparisons would still be possible.

Based on our results, we suggest that single session tDCS design may not be useful at picking up differences in motor tasks, since motor learning during early stages is confounded by random motor variability (Wu et al., 2014). Thus, multiple training sessions with concurrent tDCS or tDCS after asymptotic learning would reduce variance in scores and result in more accurate predictions.

5. Conclusion

This study suggests that single-session anodal tDCS over M1 does not significantly improve the learning of a unimanual peg-transfer task; however, these findings are not an evidence of a negative effect nor do they provide strong evidence of null effect. The findings would facilitate in designing more efficient training paradigms in the future for surgical residents.

6. Materials and methods

The study was approved by the Institutional Ethical Committee, National University of Sciences and Technology (NUST), Islamabad, Pakistan. We carried out sample size calculations based on the effect size from a previous study (Ciechanski et al., 2018) using G*power version 3 (Faul et al., 2007). A sample size of 16 was required to detect a Cohen's d of 0.40 with a power of 90%.

The data for this study were collected in the experimental room of Human Systems Lab, School of Mechanical and Manufacturing Engineering, National University of Sciences and Technology, Islamabad, Pakistan, from March 2018 to August 2018.

6.1. *Participants*

Before participation, seventeen healthy young university students (10 males, 26.24 ± 2.44 years) able to provide consent were screened. Subjects were excluded if they were left-handed, pregnant or were on medications that affect seizure threshold (e.g. tricyclic antidepressants and neuroleptics). They were also excluded if they had any metallic implants, history of seizure, history of the neurosurgical procedure, neurological condition or psychiatric condition. Inclusion criteria included right-handedness, no-prior knowledge of using laparoscopic equipment, and passing exclusion criteria. Subjects were then tested for their hand preference using the "Dutch Handedness Questionnaire". One subject was excluded because of left-hand preference. Sixteen right-handed subjects then signed an informed consent form and were enrolled in the study.

6.2. *Experiment protocol*

The experiment protocol is illustrated in Fig. 2. The subjects were required to visit the lab for two days for the experiment. The screening was done before the first visit or on the day of the first visit. The second visit of each subject was scheduled after 48 h (Boggio et al., 2008; Fregni et al., 2005) of the first visit. On the first visit, an experimenter demonstrated the use of equipment (i.e., laparoscopic graspers and the trainer) to the subjects. Afterward, the subjects had 15 min of practice session in which the subjects practiced transferring pegs. During practice session, subjects could place pegs at any place on the laparoscopic trainer and were not required to follow any particular pattern. They were also informed and given feedback about the possible types of errors, details of which are listed below in Section 6.6 Outcomes. There was a 5 min break after the practice session, during which the experimenter verbally explained the peg-transfer task to the subjects (task specific errors are explained in Section 6.4 Peg-Transfer Task and also listed in Section 6.6 Outcomes). Afterward, the subjects performed the peg-transfer task three times. The subjects were verbally reminded of the instructions before every session.

On each visit, the subjects participated in three experimental sessions: baseline, online-tDCS, and post-tDCS. The subjects performed the peg-transfer task in each session. There was a break of 15 min between the baseline and online-tDCS sessions and a break of 20 min between the online-tDCS and post-tDCS sessions. Subjects were given anodal or sham stimulation in the online-tDCS session. The order of stimulation was randomized through a simple random number generator for all subjects. In the online-tDCS session, stimulation started 10 min prior to the beginning of the task and continued for another 10 min during the task. The task lasted for approximately 10 min; therefore, the stimulation was given for a total of 20 min as it has been used in previous studies (Cuypers et al., 2013; Lefaucheur et al., 2017). Videos of the task performance were also recorded.

The study was double-blinded; therefore, the experimenter and the subjects were blinded to the stimulation condition. An independent researcher handled the tDCS device during the stimulation sessions.

6.3. *Laparoscopic trainer*

We used a custom-built digital laparoscopic trainer based on object detection sensors (Fig. S1). The position of each peg placement was detected digitally, and the timing information of individual peg placement and task start and completion time were stored. The trainer had a time resolution of 1 ms and a total of 144 locations for peg placement to allow the customization of pattern making. The trainer was placed inside a stage with adjustable height and lightning. The stage had two areas at the top for inserting laparoscopic graspers (Fig. S2). An auto-focus HD video camera was also mounted at the top of the stage. The video was visible to the subject on a screen placed approximately 1.5 m away from the subject. The subjects used a standard, double action, universal atraumatic laparoscopic grasper of diameter 5 mm and length 31 cm from GERATI Healthcare Pvt. Ltd. Pakistan, for performing the peg-transfer task.

6.4. *Peg-transfer task*

To assess the unimanual performance enhancement, we used a modified version of the peg-transfer task. Previously used peg-transfer task as originally described in (Derossis et al., 1998), uses two pegboards (placed side by side) and six pegs (triangular shaped: 1.5 cm each side; 1.0 cm internal diameter; height, 1.9 cm (Azzie et al., 2011)). The subject was required to lift a peg from the left pegboard, transfer it from laparoscopic grasper in left hand to the laparoscopic grasper in right hand, and then place the peg on the right pegboard. This is repeated for a total of six pegs and the same pegs are then transferred back from right to left pegboard using same procedure.

In the peg-transfer task, the subjects were required to place 13 pegs (cylindrical shaped; 5 mm diameter; 5 mm height) over a pre-marked pattern (Fig. 3) as quickly as possible. The pegs were available in a small container built on top of the trainer board. The subjects were required to use their right hand for holding and using the grasper to

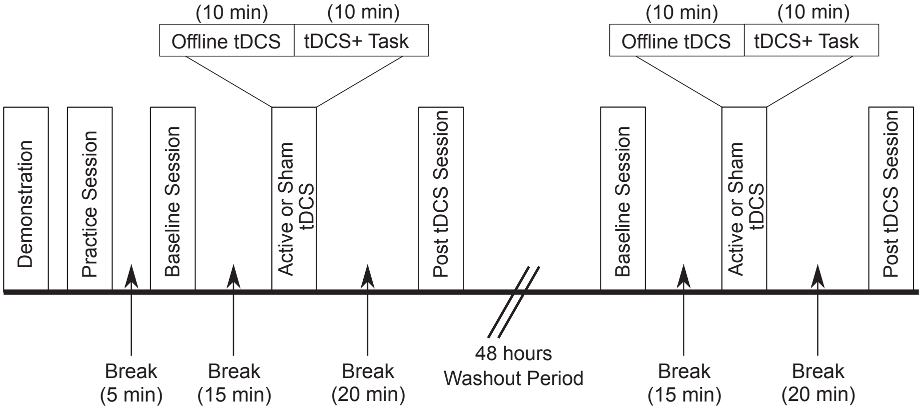

Fig. 2. Experiment Protocol.

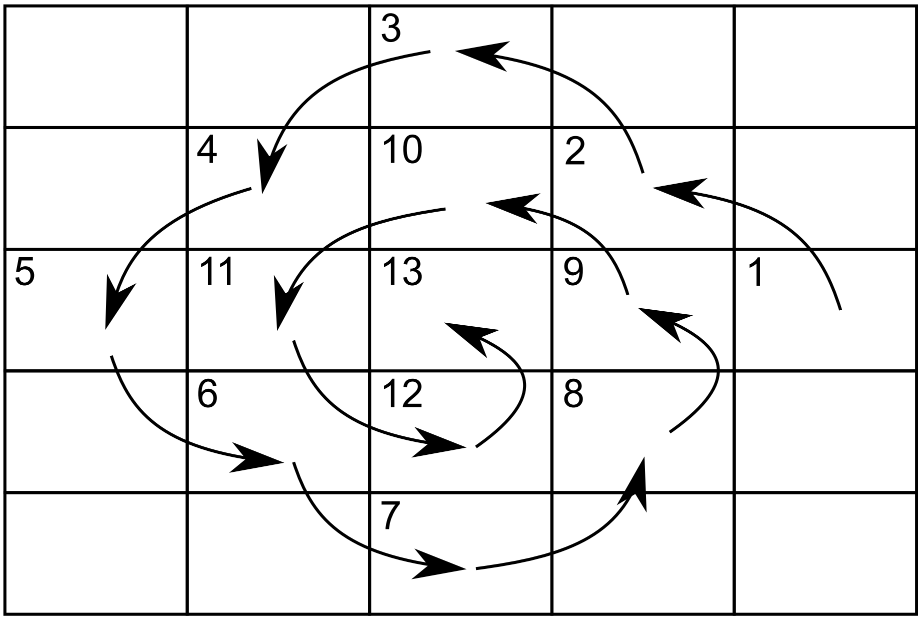

Fig. 3. Peg-transfer task. Subjects were required to start placing pegs from position 1 to position 13 in an anticlockwise manner, as depicted by arrows.

transfer the pegs. Left hand was used only to orient the face of the laparoscopic grasper in rotational plane (degrees of freedom: 360°). Since our task did not require skilled use of laparoscope with both hands and minimum use of left hand was needed, thus we have termed it as a unimanual task. Moreover, this also avoided confusion with the original peg-transfer task that involves use of laparoscopic graspers with both hands at the same time for transferring the pegs.

The order of peg placement (Fig. 3) was displayed beside the laparoscopic trainer printed on a paper. The subjects were instructed to place the pegs in an anticlockwise manner, moving from location 1 to location 13 in ascending order within the marked square on the trainer board, as shown in Fig. 3. Subjects were further instructed to follow the pattern, place pegs in horizontal orientation, not to touch or displace other pegs while placing a new peg or while retracting the grasper, failure of which would result in an error. The subjects were verbally reminded of these instructions as well as the order of placement before every session.

6.5. *tDCS*

We used Caputron, ActivaTrek's "ActivaDose 2" tDCS device for stimulation. The electrodes used as anode and cathode had a size of 3x3 cm (9 cm^2). The current intensity was 1 mA for stimulation, and thus the current density was 0.1 mA/cm^2. Anode was placed over left M1 (corresponding to electrode location C3 according to 10–20 standard of electroencephalography (EEG) electrode system), and cathode was placed over the right supraorbital region (corresponding to electrode location Fp2 in 10–20 standard of EEG electrode system). The locations were measured using a measuring tape according to 10–20 standard of EEG electrode system for each subject. Sponges of the same size were inserted inside the electrodes. Electrodes were covered in a rubber coating with a housing for placing sponges inside, and thus only the sponges came in direct contact with the scalp. Sponges were soaked in the saline solution before inserting into electrodes. Electrodes were held in place with "Caputron Universal Strap".

During anodal stimulation, the current was ramped up over 10 s, held constant at 1 mA for 20 min, and then ramped down over 3 s. In sham stimulation, the current was ramped up to 1 mA over 10 s, held constant for 1 min, and then ramped down over 3 s.

6.6. *Outcomes*

Scoring metrics for laparoscopic training tasks vary depending upon the trainer used for practice and the modality of importance (i.e., task completion time, errors, or the combination of both). Usually, task completion time is used as a score after penalizing it for the errors (i.e., Score = Cut-off time – (Task completion time + (penalty * factor)) (Berg et al., 2015; Derossis et al., 1998; Matzke et al., 2017). Cut-off time is pre-selected and is often 300 s in peg-transfer task, which is an approximate measure of task completion time used in Fundamentals of Laparoscopic Surgery (Derossis et al., 1998). Different types of penalty factors have also been used previously, such as fixed factor for all error types (Berg et al., 2015; Cox et al., 2011; Matzke et al., 2017) or different factors depending on the type of error (Cox et al., 2020). We used the same general formula to calculate the score, which we also used as our primary outcome measure. The cut-off time was selected as 600 s since our modified peg-transfer task required ten minutes approximately. The subjects were not informed about this cut-off time and they were allowed to complete the task even if they exceeded this duration. The weighting factors were decided based upon the importance of the type of error. The formula for the score is given as:

$$\text{Score} = \text{Cut-off time} - (\text{Task Completion time} + \text{Error Score})$$

Cut-off time was 600 s and Error Score was calculated as:

$$\text{Error Score} = 10 * \text{Drops (outside vision)} + 3 * \text{Drops (inside vision)} + 5 * \text{Displaced} + 2 * \text{Misplaced} + \text{Improper Transfer} + \text{Hits} + 5 * \text{Improper Order}$$

where

Drops (outside vision): Pegs dropped outside the field of vision of the camera
Drops (inside vision): Pegs dropped inside the field of vision of the camera
Displaced: Already placed Pegs displaced from their position
Misplaced: Pegs placed at an unmarked location
Improper Transfer: Pegs placed in inaccurate orientation or transferred in an incorrect manner
Hits: Nearby pegs hit while placing a peg or retracting the grasper
Improper Order: Pegs not placed in the order specified.

Higher score would mean better performance (less time taken and less errors). A score of zero was awarded if the score was negative, as reported in (Korndorffer et al., 2012) for the laparoscopic suturing task. Task completion time was available from the logged files of the laparoscopic trainer and video recordings of task performance of all subjects. A researcher, blinded to sham or active conditions, analyzed the video recordings for assessing the errors.

6.7. Statistical analysis

The score was used as the primary outcome measure, as discussed in the previous section. We used the linear mixed-effects model (LMM) for analysis in IBM SPSS Statistics version 26. The subjects were specified as a random effect, whereas “Session” (Baseline, Online tDCS, Post tDCS) and “Stimulation” (Active tDCS, Sham tDCS) were specified as fixed effects. Model fit was evaluated for covariance structures of first-order autoregressive, compound symmetry, and unstructured covariance between the repeated measures using Akaike’s information criterion (AIC). The covariance structure of scaled identity was chosen for a random effect since it assumes no correlation between each subject. The first-order autoregressive covariance structure was selected since it had the lowest AIC. The main effects of Session, main effects of Stimulation, and interaction of Session and Stimulation were calculated. For post-hoc results of the factor “Session”, we replaced “Baseline”, “Online tDCS”, and “Post tDCS” with “Session 1”, “Session 2”, and “Session 3” respectively, to evaluate learning over time irrespective of active or sham stimulation. Results were considered significant if $p < 0.05$, and multiple comparison correction for post-hoc results was done using Bonferroni correction where required. The data are presented as mean ± SD unless otherwise indicated.

Commonly available statistical packages do not provide a way to calculate effect sizes with LMM analysis. Thus, we performed supplementary analysis using repeated measures ANOVA to estimate the effect sizes. Moreover, to confirm whether our data provides the evidence of null or alternate hypothesis, we also performed Bayesian repeated measures ANOVA. The results from these are reported in supplementary materials.

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CRediT authorship contribution statement

Zaeem Hadi: Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing - review & editing. **Aysha Umbreen:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Writing - review & editing. **Muhammad Nabeel Anwar:** Conceptualization, Project administration, Resources, Supervision, Writing - review & editing. **Muhammad Samran Navid:** Conceptualization, Methodology, Resources, Supervision, Validation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.brainres.2021.147656.

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