A Digital System for Evaluating the Effect of tDCS on Laparoscopic Surgical Skill Acquisition

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Dedicated to

All the Guides and Beacons of Hope

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Aysha Umbreen

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ABSTRACT

Background: Transcranial direct current stimulation (tDCS) is a powerful non-invasive brain stimulation technique, which can be used in treatment of wide variety of psychological and physical disorders. It is still a vast field to explore, as there are a number of different variations in protocol with variety of different effects.

Objective: There were two objectives of the study. First was to design a digital laparoscopic trainer. Second objective was to evaluate the effect of transcranial direct current stimulation on laparoscopic peg transfer task being performed on the designed digital trainer.

Methodology: A digital trainer was designed using Arduino Uno microcontroller and optical sensors as bead detectors. Trainer has the ability to detect 144 beads. For tDCS study, a double blind crossover study design was selected for experiment in which each subject underwent both Active and Sham treatment. The treatments were separated by a period of 48 hours. Subject completed the laparoscopic peg transfer task in 3 sessions on both treatment days with one session being baseline and other session was post-tDCS.

Results: Repeated measures ANOVA showed a significant different in baseline (active) and active tDCS session with $p=0.002$. However, contrary to expected results sham tDCS session was also significantly different from its baseline with $p=0.01$.

Conclusion: This study suggests that tDCS may play a role in performance enhancement of a peg transfer task when applied over M1 region contralateral to dominant hand however the results may be task specific to the type of task used in the study.

PART I

INTRODUCTION
&
LITERATURE REVIEW

1 Introduction

Neurological Disorders are diseases related to brain, spinal cord and nerves that establish a connection between these parts. It has been reported in "*Neurological disorders: Public health challenges"* that 50 million people suffer from epilepsy and 24 million from Alzheimer and other dementias. Neurological disorders affect people in all countries. An estimated 6.8 million people die every year because of neurological disorders. About 10% of population in Pakistan are living with some kind of a neurological disorder that includes strokes, migraines, Parkinson's, epilepsy and Alzheimer's disease [1]. It shows that despite major advancements in the treatments of such disorders, a lot of work is still required. There are many limitations to current pharmacologic treatments (i.e. adverse effects or requirement of tailored medicine), physical and behavioral treatments (i.e. dependent on administrator and cooperation of patient). Brain stimulation techniques however can be used to modulate neuronal activation patterns and to restore balance in the targeted neural network. Invasive brain stimulation techniques such as deep brain stimulation and cortical stimulation are established techniques for pain and Parkinson's whereas work for treating stroke and epilepsy is still underway [2]. However, non-invasive brain stimulation techniques such as TMS and tES looks more promising as it saves from opening up a patients skull. A recent study reported that TMS is the only non-invasive brain stimulation technique that has been approved officially and is being used for treatment of depression only. Thus, it is believed that after refinement of these techniques and improvement in employed protocols, more beneficial effects can be produced using these techniques, and non-invasive brain stimulation will be used as an approved therapeutic approach [3].

Non-invasive Brain Stimulation Techniques

2 Transcranial Magnetic Stimulation (TMS)

TMS is a powerful tool for non-invasive brain stimulation and it is still under development and is not widely employed. A pulsed current is passed through a magnetic coil that results in magnetic field perpendicular to the coil. This magnetic field induces electric field perpendicularly, which further causes current to flow in loops. So there is more strength along the circumference of the coil and very weak at the center of coil. A number of shapes are used for magnetic coils from which round coils are known for being more powerful whereas eight-shaped coils are known for focal strength [4].

TMS is categorized as Repetitive TMS (rTMS) and Single-pulse TMS. Repetitive TMS (rTMS) is a type of TMS in which stimulation is done by delivery of multiple pulses in a short time. rTMS can result into long lasting changes in neural network activation. It is also known to cause seizures in healthy individuals that can be avoided by following safety protocols. Single-pulse TMS, however, is more commonly used and relatively weak as compared to rTMS. Effects produced by single-pulse TMS are typically short lived [5].

TMS can be used to evaluate the conduction speed in neuronal pathways to study the neurological disturbances in patients with various neurologic and degenerative diseases [6]. Rapid rTMS is known to induce motor excitability whereas slow Rtms can reduce excitability [7, 8]. Reaction times in Parkinson's patients were also improved as a result of TMS [9]. Studies have also shown that TMS can be impact the mood in healthy individuals and can also be used as a treatment for depression [10].

3 Transcranial Electrical Stimulation (tES)

Transcranial electrical stimulation (tES) is a non-invasive brain stimulation technique in which weak electrical current is provided for short to moderate period with scalp electrodes. In recent years, tES has surfaced as a promising technique for therapy of various neurological disorders that include depression [11], post-stroke rehabilitation [12, 13] and pain [14]. Although tES is known to produce useful results but establishment of efficient protocols is still required. The protocols are controlled by parameters that include the selection of protocol based on current type, current intensity, polarity of stimulation, stimulation duration and phase information. Besides these the optimum electrode size, shape, material and montage selection is required to produce the best results [15]. There are four major electrode montages [16] based on the targeted brain hemisphere and the total number of electrodes which are:

1. Unilateral: Stimulation on only one brain hemisphere
2. Bilateral: Stimulation on both hemispheres
3. Midline: Stimulation on midline of brain
4. Dual Channel: Two independent electrodes

There are several types of transcranial electrical stimulation based on the type of current being used (Figure 1). Their details are discussed below:

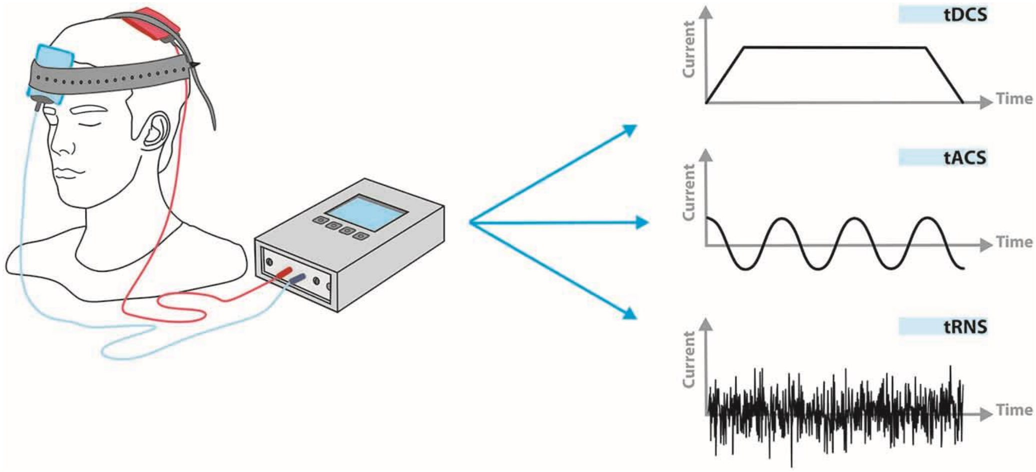


Figure 1 Types of tES [17]

3.1 Transcranial Random Noise Stimulation (tRNS)

Transcranial random noise stimulation (tRNS) technique is a modified form of transcranial alternating current stimulation (tACS). In tRNS, alternating current with continuously varying intensity and frequency in randomized manner is used for biphasic stimulation. tRNS can either be low frequency (range:0.1 Hz-100 Hz) or high frequency (range:100 Hz-640 Hz) with complete spectrum ranging from 0.1 Hz to 640 Hz and different forms of noise can be used [18, 19]. The stimulation current follows a zero mean and variance Gaussian curve with 99% of current generated lying in range of ±1mA [20].

tRNS enhances the excitability of M1 region which is comparable to the excitation produced by anodal tDCS and the resulting effects can last up to 1-1.5 hours [19, 21-23]. Another study showed that tRNS over M1 enhanced motor skill acquisition in contrast to sham stimulation [24]. tRNS is also found to be intensity dependent [22]. A study has shown that high frequency tRNS significantly improves perceptual learning in a task as compared to anodal, cathodal or sham tDCS [25]. These studies show that application of tRNS over various brain regions can produce long lasting facilitating effects.

3.2 Transcranial Alternating Current Stimulation (tACS)

tACS is a method of non-invasive brain stimulation in which externally applied oscillating current can directly modulate the brain oscillations. tACS can cause synchronization or desynchronization of brain oscillations producing positive or negative effects accordingly [26].

In addition to application of alternating current instead of direct current, tACS has many other functional differences as compared to tDCS. One of the major difference is the interpretation of anodal and cathodal electrodes. In tACS, cortical excitation is quite is different from tDCS because during half cycle of stimulation one electrode is anode and other is cathode whereas during the remaining half cycle the electrode polarities are reversed. Maximum current flow occurs only during peak of the phase. So overall membrane potential is not modified. This suggests that tACS is not suitable for long lasting effects however it can be used to produce online excitation of different brain regions [20].

In theory, based on previous studies, some of the tDCS findings may also hold for tACS [27]. However when tACS is applied over motor cortex various studies show varying results. Motor cortex excitation is either single or multiple frequency tACS dependent [28, 29]; tACS can also result in inhibition of motor cortex [30]. tACS can produce diverse range of behavioral effects. tACS in the beta frequency range slows the voluntary response and enhances in the gamma frequency range [31, 32]. tACS on visual cortex can result in its excitation which is associated by the detection of phosphenes when stimulation is applied [33, 34]. Studies have shown that tACS can improve performance in tasks that involve working memory [35] and it can also improve decision making in during risky conditions [36]. tACS studies uptill now however lack the support of electrophysiological evidence [37]; tACS with various frequencies have resulted in no effect on EEG [38].

3.3 Transcranial Direct Current Stimulation (tDCS)

Transcranial electrical stimulation methods go way back to 19^{th} century and it has also been reported in 1802 that direct current application can have beneficial effects [39]. After credible information of plastic changes produced by tDCS, using TMS studies, it'S use became more reliable [40]. tDCS was then studied in detail in respect of its various controlling parameters and duration of its effects [41].

tDCS is application of weak dc electrical currents by two electrodes that are Anode (positive) and Cathode (negative). A DC stimulation ranging from 0.5 to 2 mA is applied on a brain location with anode or cathode. Location of reference electrode is selected accordingly. The effects can last up to as long as 1-2 hours depending on the duration of stimulation [42].The resulting effects of tDCS also depend on the polarity of these electrodes. Anodal stimulation is generally considered to enhance the evoke potential as compared to cathodal stimulation which inhibits the evoked potential [39]. The electrodes used have size ranging from 25-35 cm^2.

tDCS is usually applied and widely used in different forms which are discussed below.

3.3.1 Anodal Stimulation

Positive and negative electrodes are used in their usual polarity. A number of studies have related positive effects of anodal stimulation to motor performance, cognitive control and motor learning in healthy individuals [43]. Anodal stimulation causes excitation in motor evoked potentials (MEP's)[41]. Anodal stimulation is also reported to have task dependent effects on motor learning and memory formation [44].

3.3.2 Cathodal Stimulation

The electrode polarity is reversed in this case. Anode serves as a reference electrode and cathode is planted at the stimulation site. Cathodal stimulation is generally considered to inhibit the motor evoked potentials (MEP's) [41]. However, various studies have reported positive effects of cathodal stimulation. Cathodal stimulation is reported to improve language comprehension in stroke patients [45]. Cathodal stimulation is also considered to improve attention and act as a noise filter to enhance cognitive performance [46]. It has also been reported that cathodal stimulation can prove successful results in treating migraine patients [47].

3.3.3 Sham Stimulation

Sham stimulation session mainly serves as a control or for blinding purposes of tDCS experiments. In sham stimulation, current is ramped up and then down in just the start and end of the task so that participants can feel the itching sensation. The current intensity is the same; just the current duration is reduced to a total of about one minute or even less [48]. This stimulation is for short amount of time so there are no after effects [43].

3.3.4 Off-line and On-line tDCS

tDCS can also be characterized as off-line or on-line tDCS. They are mainly associated with the period of stimulation. If stimulation is provided when task is not being performed, either before or after the task, such type of stimulation is called off-line stimulation. Whereas, if tDCS is applied during the task performance then it is categorized as on-line tDCS stimulation.

4 Motor Learning

Motor learning is a conscious and unconscious learning of a skill or task that involves body movements. Body movement allows us to move our limbs and enables the corresponding sensory receptors to receive information. This sensory input information is mostly task specific [49]. Repetition of motors tasks allows our brain to create and remember the specific motor patterns that are easy to recall after some time. Best example of this unconscious motor learning is when we learned to walk during childhood. Another example of this unconscious learning is to play a specific music instrument for example a piano or violin. Repetitive motor movement of fingers fine tunes the motor skill patterns which can recalled later more easily and without conscious effort [50].

There is conscious brain involvement during the initial phase of motor learning process but the necessity for this conscious involvement vanishes with time as the learning of the skill improves thus making it part of the learning process. The brain parts and mechanisms involved in this learning process are rather complex[50].

Motor learning depends upon practice and feedback and it leads to skill acquisition when a person moves from simple tasks to complex tasks and improves upon them. A person's age, motivation, learning style and cognition affects the learning process and improvement of the skill [51].

4.1 Stages of motor learning

There are three main stages in motor learning [52].

4.1.1 Cognitive Stage

Cognitive stage is the earliest stage of learning. During this first stage, learner gets an understanding of the skill and information regarding its objective. Conscious attention of the learner is consistently required in this stage, as learner has to experiment different strategies to obtain optimal results. Because of these high demands, they take longer to perform the skill and are inconsistent in their performance [53].

4.1.2 Associative Stage

In associative stage of moto learning, learner starts to improve and optimize his movements and has full knowledge of what to achieve and how to do that. In this stage learner leans more toward feedback from proprioceptive sensation and becomes less dependent on visual information [52].

4.1.3 Autonomous Stage

Autonomous stage is the final stage of motor learning and is also termed as motor stage [54]. Learner performs movements more fluently and errors in movements are reduced to minimal. This stage puts a lot less conscious demands of attentions on learner [53].

4.2 Types of Motor Learning

Motor learning is divided into two major types based on learning mechanism. These are:

1. Explicit Learning
2. Implicit Learning

4.2.1 Explicit Learning

Explicit learning can also be called declarative learning as it involves memorizing facts. Therefore, learner has to be actively conscious in order to learn something explicitly and thus it makes heavy demands on working memory [55]. Learners distinctly remember and explain what they have learned in case of explicit learning [55]. The information obtained by learners are first encoded when obtained first time, which is available later when needed. The obtained information is consolidated and is stored for a longer period [56].

4.2.2 Implicit Learning

Implicit learning is a type of learning in which information is obtained in an indirect manner and it is not possible for learners to verbally explain that what they have learned. It makes a lot less demands on attentional resources of the learner [55]. Implicit learning is considered less flexible as compared to explicit learning and it is not possible for knowledge gained about one task to be transferred to another similar task. Even if there is some transfer, the performance levels will surely decline [57].Attention in implicit learning is also attracted and not directed so there is a significant role of observation instead of testing of a pre-made hypothesis [57]. Knowledge gained through implicit is considered more robust and it has a longer retention period as compared to explicit learning. Implicitly gained knowledge remains independent of age related or any psychological disorder effects [57, 58].

5 Relationship between tDCS and Motor Learning

tDCS has been established as a safe non-invasive brain stimulation technique. Further studies are required as the interest in tDCS is increasing, based on its potential for clinical studies. tDCS is being used in numerous studies ranging from learning of new and novel techniques to reacquiring lost skills due to some disorder. Acquisition of a motor skill can take from days, weeks and up to months and diminish over time. So techniques like tDCS that can enhance skill learning as well as retention are of great importance.

Motor skill learning of a sequential tapping task can be enhanced by a single tDCS session however results of performance are more significant after an interval of 24 hour [59]. This shows that tDCS has no effect on motor learning during early stages. However, contrary to this study there is evidence that supports that tDCS can also enhance motor learning during early stages [60]. A number of reasons that include inadequate stimulation protocol, electrode size, stimulation intensity and stimulation duration plays important role on results of the studies. Various studies show that multi-session tDCS can improve learning of a motor task when evaluated post-intervention and it can also help improve retention of skill [59]. A number of motor tasks including "Purdue Pegboard Test (PPT), Jebson-Taylor test and Serial Reaction Time Task" were tested in a study for the effect of tDCS on motor learning in children. tDCS enhanced the motor learning in all tasks as compared to sham stimulation and the effects of learning were also present when re-tested after 6 weeks which also suggests a relationship of tDCS with retention [61]. In addition to sequential learning, application of tDCS can also support in visuo-motor coordination tasks. tDCS over exstrastriate visual areas and motor cortex improves the learning of a reaching movement task using a manipulandam [62]. The discussed studies have employed unilateral tDCS. A study has shown that Bilateral M1 stimulation can also facilitate learning of Purdue Pegboard Task and multiple visuo-motor tasks (i.e. Visuomotor Grip Force Tracking Task and Visuomotor Wrist

Rotation Speed Control Task). Performance improvement was maintained post-intervention depicting online learning and was also maintained over weeks which depicts retention [63]. Various tDCS studies have shown that tDCS can be used as a motor performance enhancement tool in stroke patients [64, 65].

6 Objectives

As discussed in previous sections, tDCS is being employed in number of studies for performance enhancement, stroke rehabilitation, treatments of various psychological disorders and for reducing the time for acquisition of new skills.

Laparoscopic surgery is a minimally invasive surgery that is performed with the help of small incisions in abdominal cavity. Doctors are usually trained on a laparoscopic trainer that contains various exercises. These exercises and training is performed in front of trained proctors who evaluate the performance manually either with questionnaires or with the help of video tapes [66-69].

Moreover, previous tDCS based laparoscopic have suggested mixed conclusions. tDCS has helped in improving some tasks whereas some tasks has no effect[70, 71]. So, we propose that tDCS can enhance the performance in a laparoscopic peg transfer task based on number of studies that elicit positive effects on motor learning and visuomotor performance enhancement [60-62, 64]. Therefore, our study had following objectives.

- To Design a digital laparoscopic trainer for digitally recording the time of laparoscopic peg transfer task to automate the process and remove the necessity of a trained proctor.
- To evaluate of transcranial direct current stimulation on laparoscopic peg transfer task

PART II

METHODOLOGY

7 Methodology

A number of standard laparoscopic training tasks are used for surgical skill acquisition training (Figure 2).

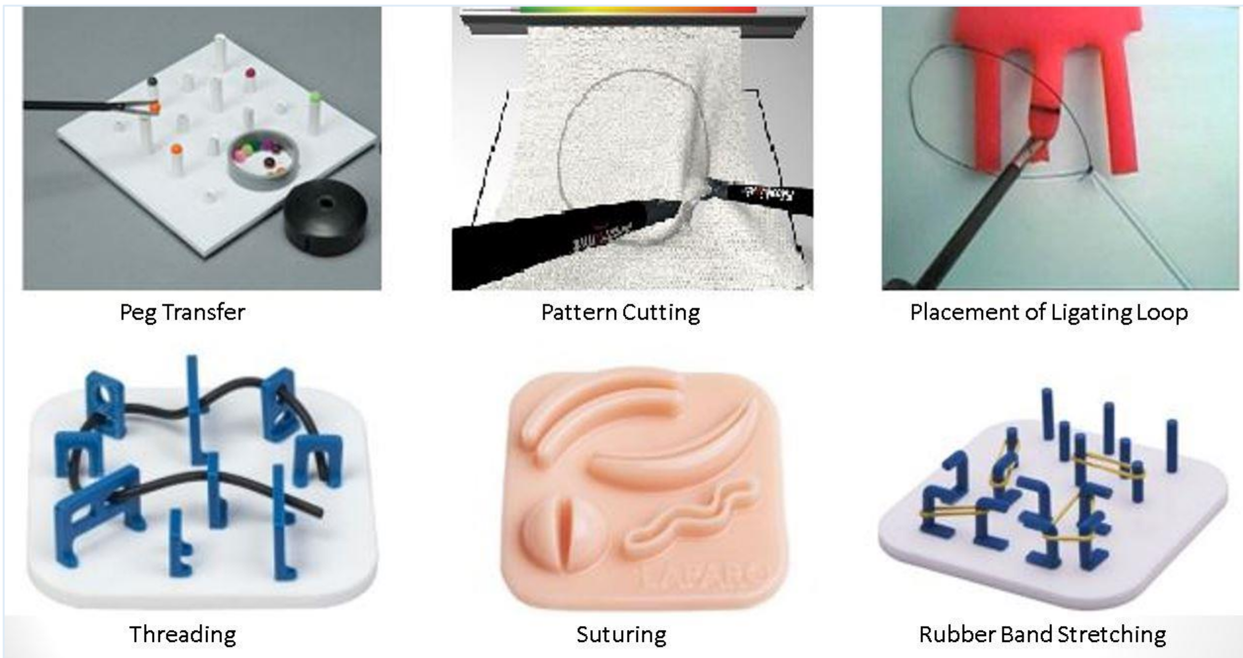


Figure 2 Types of Laparoscopic Training Tasks

Laparoscopic peg transfer task was adopted to evaluate the effects of tDCS on laparoscopic surgical skill acquisition. Task was modified in order to digitize evaluation setup.

7.1 Object Detection Technique

Laparoscopic trainers previously available use trained proctors that assess video-tapes for performance evaluation. In order to increase the accuracy of performance evaluation a digital system was required. In laparoscopic peg transfer task, position of bead placement and time taken to place the bead is required for performance assessment.

A reflective optical sensor was selected for detection of bead placement. The sensor contains both IR emitter and phototransistor in the same leaded package that blocks visible light. The wavelength of IR emitter is 950 nm that is not in visible spectrum.

7.1.1 Working Principle

IR emitter transmits rays that are reflected from a surface. The reflected rays are detected by the phototransistor. There is no cross talk or noise in normal condition and phototransistor gives minimal output.

The output voltage value depends on the color of surface that is reflecting the rays. White reflective surface maximum voltage output whereas black gives minimum voltage output. Sensor was tested in various configurations and optimum resistor values was selected based on the detecting distance required. The sensor configuration employed in finalized circuits is given in figure XX.

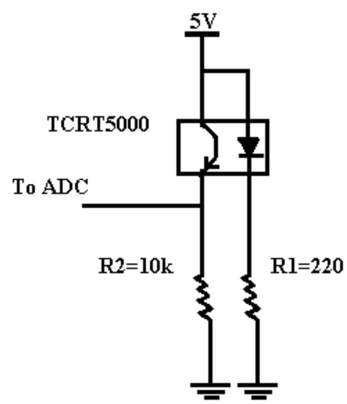


Figure 3 Circuit Configuration

7.2 System Design

The trainer is composed of three main components that are given below:

1. Sensor Board
2. Multiplexer Boards
3. Mux-Selector Board

Details of these components are given below.

7.2.1 Sensor Board

Sensor board is composed of 144 sensors. The sensors are arranged in an array of 12x12. Therefore, there are 12 rows and 12 columns of sensors. Each sensor is connected according to the configuration discussed in section 1.2.1.

Circuit is designed keeping in mind the restriction of equidistant sensors across the board that is normal practice in some standard trainers. Sensor distances are given below:

Horizontal Distance: 0 cm

Vertical Distance: 1 cm (center to center)

There is no horizontal distance between sensors on the “sensor board” and there lead packages are connected to each other. However, subject board for bead placement has different dimensions. These dimensions are only for sensor board design. Complete board is cut in 14x14 cm dimensions to adjust power connection. The sensor orientation in circuit is alternate due to routing limitations however; it has no effect on product (See section 11.3 for schematics of sensor board). The circuit figure in final form is given below.

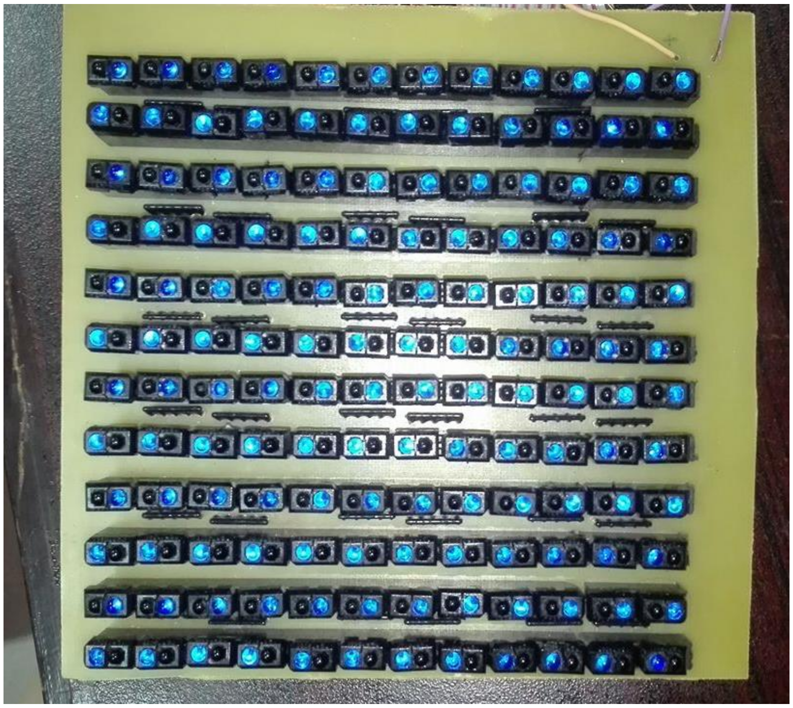


Figure 4 Sensor Layout

7.2.2 Multiplexer Boards

Arduino UNO microcontroller is used for reading sensor outputs due to size limitation. So in order to read 144 sensor outputs a set of multiplexer boards are designed.

9 multiplexers of 16:1 configuration are used to read 144 sensors. Each multiplexer circuit board is separately designed and stacked over each other to reduce the size of setup, decrease circuit complexity and ease of debugging.

Each board reads 16 sensor outputs. The selection bits of each board are common to each other and are connected to digital pins 2-5 of Arduino UNO. Pins 0 and 1 are not used as they are for serial communication. Therefore, each board continuously reads the 16 outputs based on the selection bit configuration. The final circuit stack is shown in figure. The 9 multiplexer boards are reading 144 outputs in parallel and to select one of these 144 outputs a selector board is designed. See section 11.1 for schematics.

Figure 5 Arduino, Selector Board and Mux Boards in Order from Left to Right

7.2.3 Mux-Selector Board

A mux-selector board is designed in order to select one of the 144 outputs being read in parallel by multiplexer boards. Delay between reads can be altered by Arduino code. Selection bits of mux-selector board are connected to analog pins A0-A3. Selector board reads 16 outputs of each board sequentially. The outputs of 9 multiplexer boards are fed into mux-selector board and one of these 9 outputs gets selected on Arduino's analog pin A4. Mux-selector board is also designed in a way that it can be stacked with rest of the circuits. Arduino UNO microcontroller is also mounted on mux-selector board shown in Figure 5. For schematics of mux-selector board, see section 11.2

Figure 6 demonstrates the complete system architecture. In addition, complete circuits connected with each other are given in figure 7 and finished form is provided in figure 8.

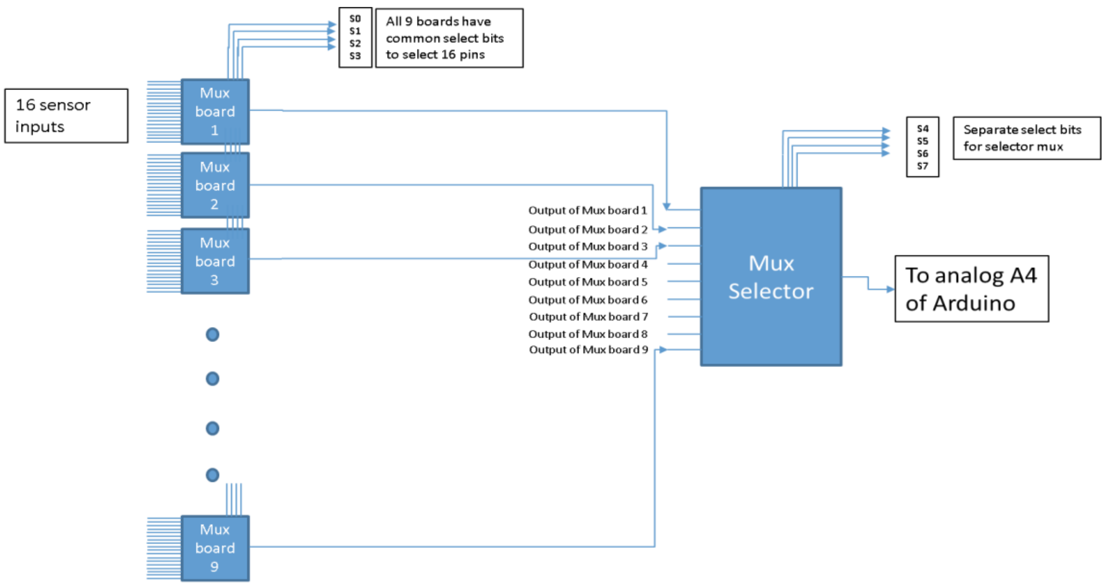


Figure 6 Complete System Architecture

Figure 7 Final Sensor Board and Mux Boards Connected

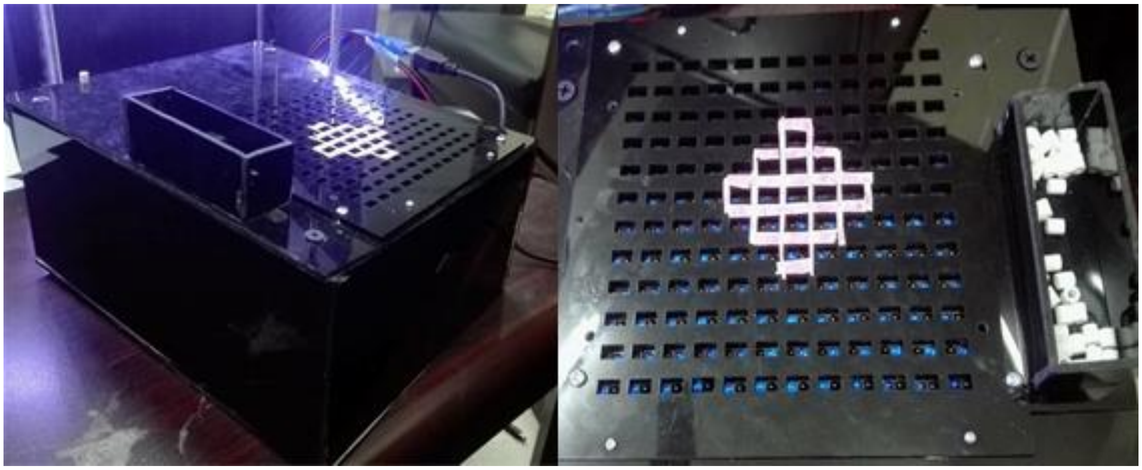


Figure 8 Circuits Enclosed with Subject Board

7.2.4 Subject Board

Subject board contains housing for bead placement as shown in figure above. Dimensions of subject board are following:

1. Horizontal square size: 7 mm
2. Horizontal distance between two squares: 3 mm (edge to edge)
3. Vertical square size: 4 mm
4. Vertical distance between two squares: 6 mm (edge to edge)

7.2.5 Power Specifications

Arduino is powered through USB jack. All multiplexer boards and sensor board are connected to an external DC power supply rated at 5V 4A. Sensor board draws current ranging from 1.9 A to 2.2 A.

7.2.6 Complete Setup

The digital trainer system was placed inside a stage that was designed to insert laparoscopic graspers. The stage has an adjustable height and it is covered from three sides. An autofocus HD video camera mounted at the top and the video was visible on a screen that was placed at approximately 1.5 meters away from the subject. LED’s are mounted inside the walls of the stage to provide lightning inside the stage.

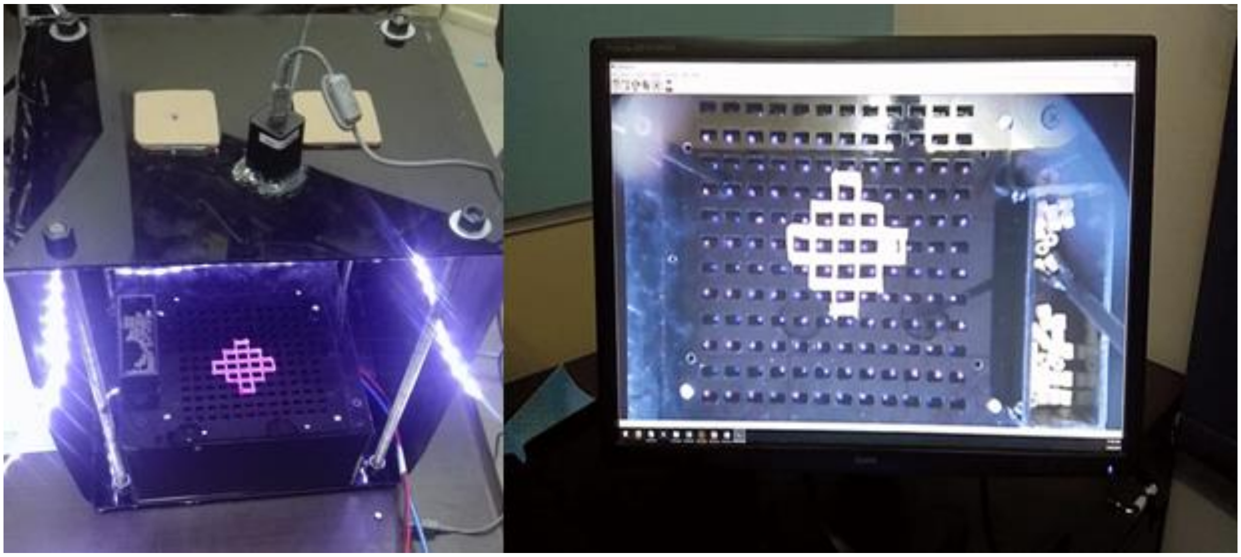


Figure 9 Complete Trainer (left), Video feed of Subject Board on Screen (right)

7.3 Study Protocol

7.3.1 Experimental Overview

The study design employed was a longitudinal cross over study. The study was double-blinded and each participant received both anodal and sham tDCS. Order of these sessions were counterbalanced and randomized for all the participants. Both anodal and sham stimulation sessions were separated by 48-hour wash out period to avoid any carry over effects. Experiments were organized in experimental room of Human Systems Lab in SMME department of National University of Sciences and Technology (NUST).

7.3.2 Participants

16 participants were recruited for the study. All participants were graduate and under-graduate university students. Each participant was screened for any kind of medical disorders, substance abuse or dependence, use of CNS medication, psychiatric and neurological disorders (including surgery, tumor or intracranial metal implantation). All participants gave there informed consent prior to be enrolled in the study. Participants was tested for their hand preference and dexterity using “Dutch Handedness Questionnaire”. Based on questionnaire results all subjects were dominantly right handed. All participants had normal hearing and corrected to normal vision. Participants were naïve to experimental procedure and purpose of the study.

7.3.3 Experiment Sessions

Experiment was composed of two days and each day participants followed the same session design. Participants completed three sessions on each day that are:

1. Baseline session
2. tDCS session
3. Post tDCS session

Each participant performed a practice session on first day for 15 minutes to familiarize with the experimental procedure. A timing diagram showing timing detail of sessions is given below. In all three sessions, subjects performed the same task. Bead positions were marked on the trainer as well as on separate sheet pasted alongside trainer for subjects and order of their placement was also marked. The placement was supposed to be in counter-clockwise manner.

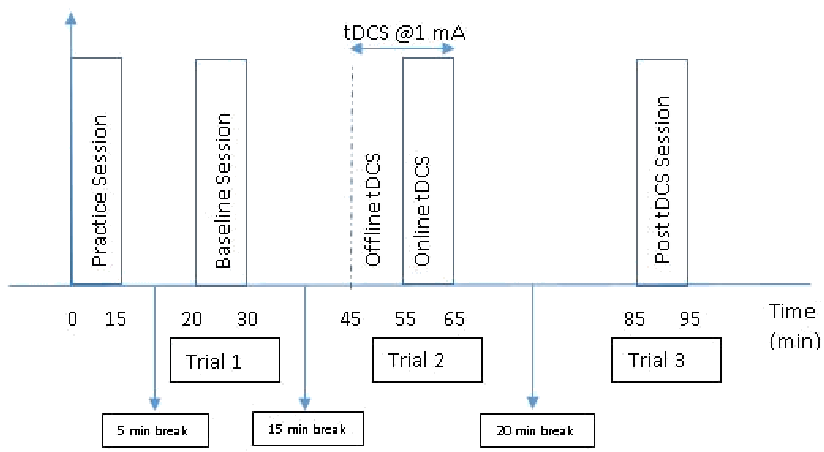


Figure 10 Experiment Sessions and Timing Details

7.3.4 tDCS Protocol

"ActivaDose II" device was used for stimulation. Electrode size of both anode and cathode was 3x3 cm. 1 mA current was used for stimulation. The current density was 0.1 mA/cm^2 . Active electrode was placed over C3 location (contralateral to dominant side) and reference electrode was placed on supraorbital region (contralateral to C3) that is Fp2 location. The location were measured according to 10-20 EEG system. Sponges soaked in saline water were used as conducting medium between the scalp and the electrodes.

Figure 11 tDCS Device with sponge electrodes (left), Subject with Electrodes Attached at C3 and FP2

In anodal tDCS session current was ramped over 10 seconds and held constant at 1 mA for 20 minutes and then ramped down over 2-3 seconds. During sham stimulation, the current was ramped up over 10 seconds and held constant for 1 minute and they ramped down over 2-3 seconds.

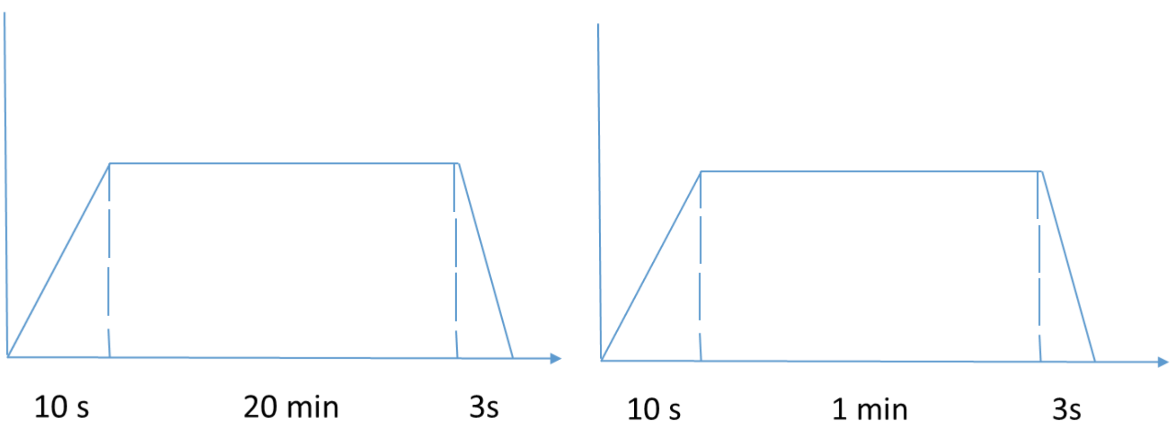


Figure 12 Active Session Current Graph (Left), Sham Session Current Graph (Right)

7.3.5 Experimental Task

Subjects were required to complete a pattern marked on subject board in order given in following figure. The order was explained to the subjects and it was also written on the shape placed besides the setup to remind (in case someone forgets during experiment).

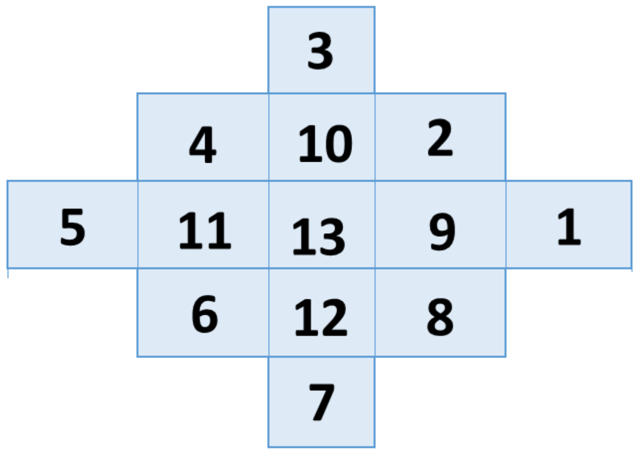


Figure 13 Bead Placement Pattern Shape and Order

The subjects were instructed to place the beads in the order of numbering i.e. anti-clockwise, starting from 1 and ending at 13. So subjects were required to place 13 beads. Beads were placed over the subject board and the digital system installed below was used for the recording of timing information. Time of placement of each bead and the position of bead placement was recorded; however, the main aim was time of placement that is used in the analysis.

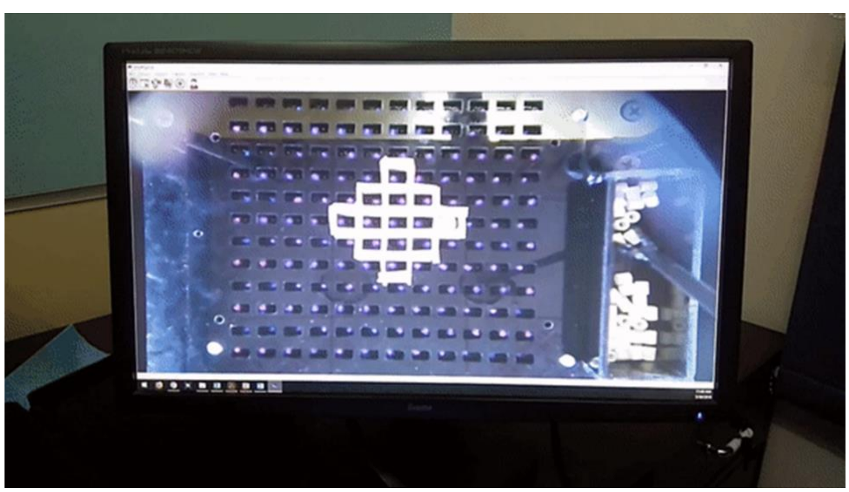


Figure 14 Video Feed from Camera Attached on Trainer

7.4 Statistics

Analysis of the acquired data was done by STATISTICA 10 software (Statsoft, Inc.). The subjects were assessed based on their improvement in time to complete the task in different stimulation sessions. Data is recorded in terms of seconds. Each subject's bead placement time was averaged and mean bead placement time was the outcome measure.

Subjects' sessions were divided into two days. Sessions on each day were composed of baseline, tDCS (active or sham) and post-tDCS session. Baseline was selected as control session to evaluate the performance improvement across sessions. The study employs a crossover design so each subject acts as a control for himself.

Shapiro-Wilk's test and box and whisker plot was used to determine the normality of data. Data was considered normal if p value>0.05 and if there were no extreme outliers. Repeated measures analysis of variance was performed in which the three sessions (baseline, tDCS (active or sham), post-tDCS) were dependent variable of all subjects. Repeated measures analysis of variance was separately performed for active and sham sessions to check the overall effect. Post-hoc comparisons were further used to evaluate the individual differences between the three sessions. The difference in mean time values were considered significant if $p<0.05$.

PART III

RESULTS

8 Results

Results of Repeated Measures ANOVA with Active tDCS

8.1.1 Normality Tests

Box and whisker plots shows a minor outlier in baseline session and no extremes.

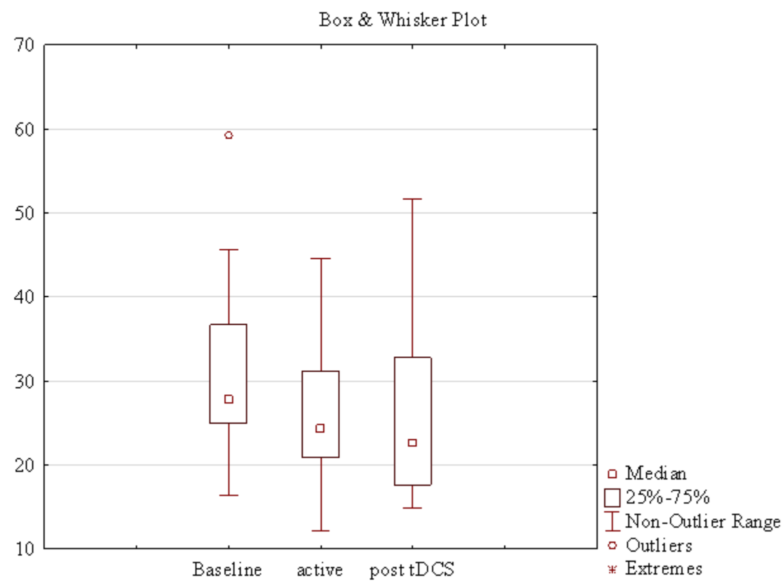


Figure 15 Box and Whisker Plot of Baseline, Active, Post-tDCS session on day of Active Session

8.1.2 Normality Plot of Baseline of Active Group

P value=0.057 of Shapiro-Wilk's test shows that the data is normal (p>0.05).

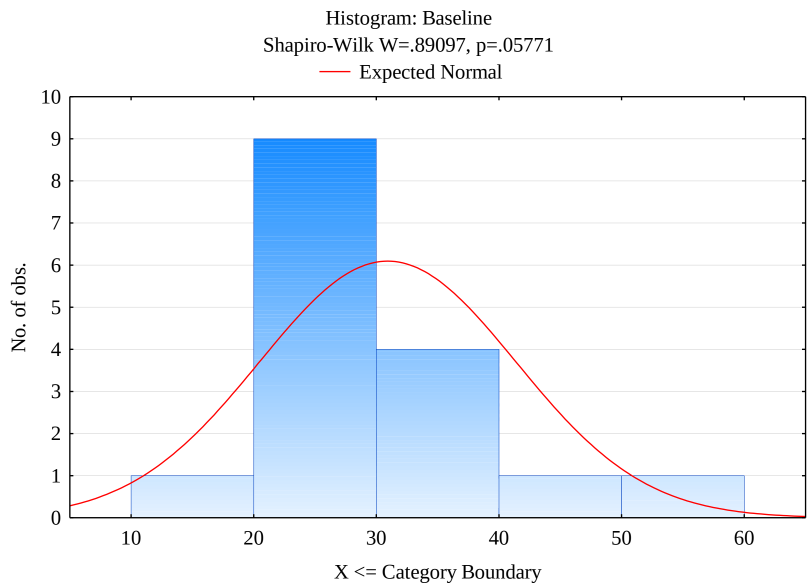


Figure 16 Normality Plot of Baseline of Active Group

8.1.3 Normality Plot of Active tDCS Session

P value=0.84 of Shapiro-Wilk's shows that the data is normal ($p>0.05$).

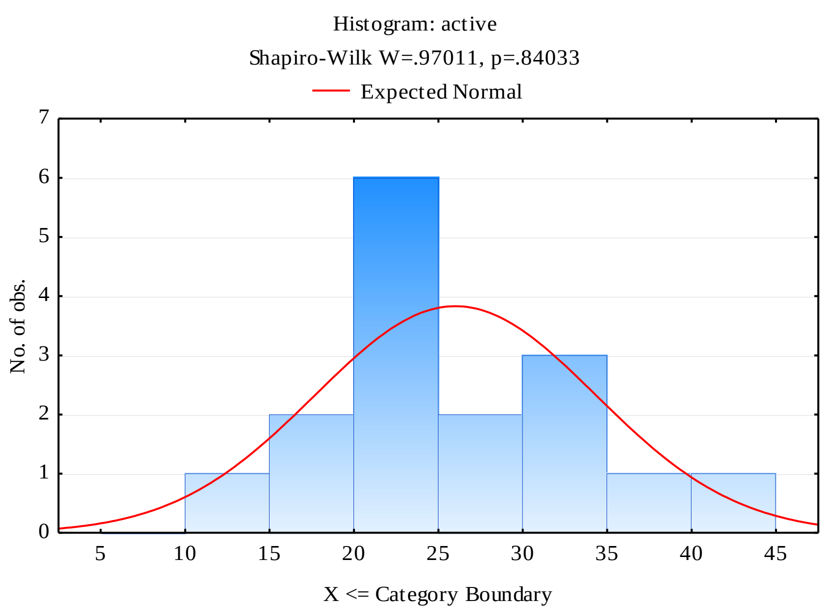


Figure 17 Normality Plot of Active tDCS Session

8.1.4 Normality Plot of post-tDCS Session of Active Group

P value=0.03 which suggest that data is not normal ($p<0.05$). Using median and iter-quartile ranges, it was determined that there was a minor outlier so it was not removed from the data.

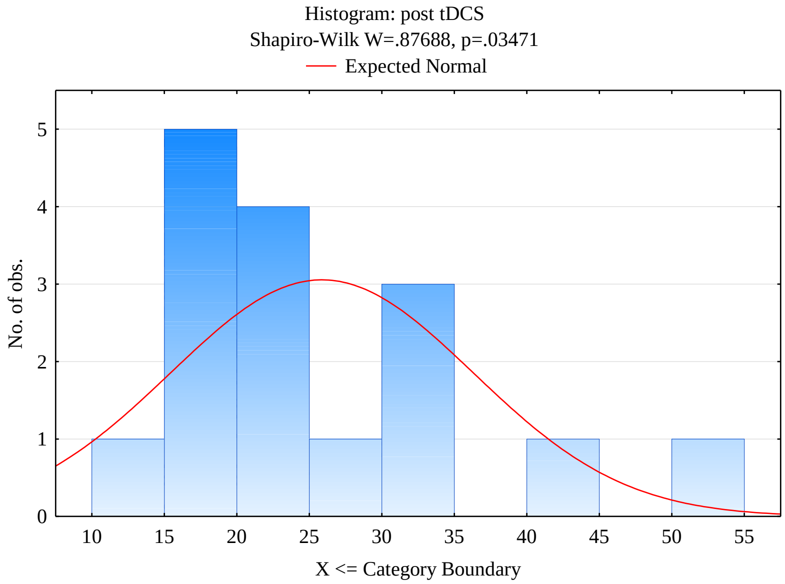


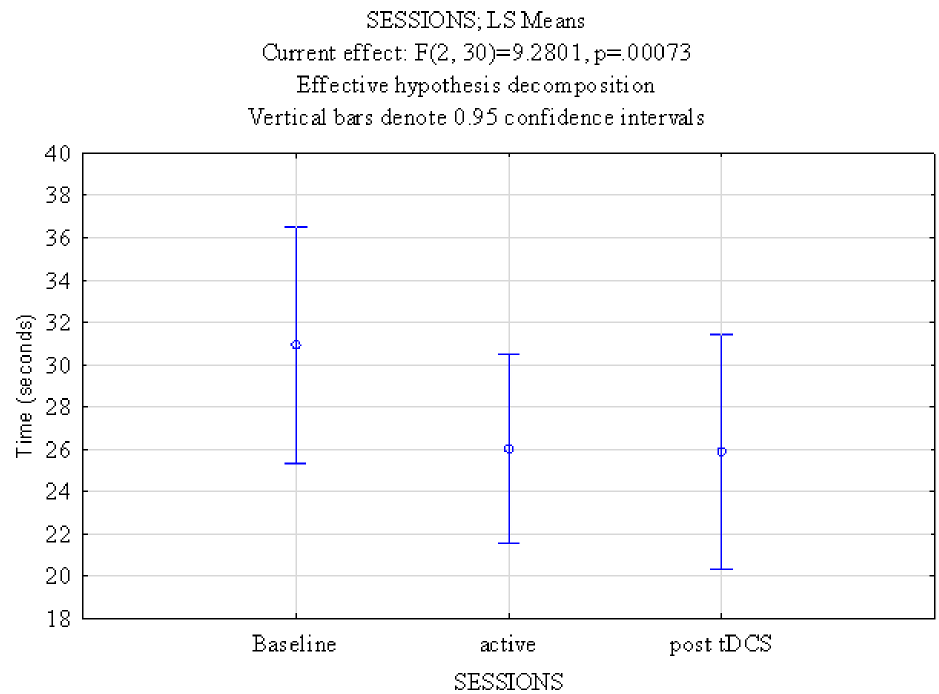
Figure 18 Normality Plot of post-tDCS Session of Active Group

8.1.5 Post-Hoc Analysis Results

Repeated measures ANOVA comparison between baseline, active tDCS and post-tDCS resulted in in $F(2,30)=9.2801$and $p=0.0007$ ($p<0.05$) which shows that a significant difference in performance exists across the three sessions (Figure). To evaluate that which two groups differ from each other, post-hoc analysis was performed using Tukey's HSD test. Results of Tukey's test comparison are discussed below.

Baseline and Active Session

Tukeys's HSD test shows that a statistically significant difference in performance exists between baseline (Mean time= 30.927 seconds) and active tDCS sessions (Mean time= 26.015 seconds) with $p=0.002$ ($p<0.05$).



SESSIONS; LS Means (active_new.sta)
Current effect: F(2, 30)=9.2801, p=.00073
Effective hypothesis decomposition

Cell No.	SESSIONS	Time(s) Mean	Time(s) Std.Err.	Time(s) -95.00%	Time(s) +95.00%	N
1	Baseline	30.92745	2.618034	25.34724	36.50766	16
2	active	26.01495	2.082768	21.57563	30.45426	16
3	post tDCS	25.86883	2.611819	20.30187	31.43579	16

Tukey HSD test; variable DV_1 (active_new.sta)
Approximate Probabilities for Post Hoc Tests
Error: Within MS = 14.294, df = 30.000

Cell No.	SESSIONS	{1} 30.927	{2} 26.015	{3} 25.869
1	Baseline			
2	active	0.002674		
3	post tDCS	0.002026	0.993504	

Figure 19 Repeated Measures ANOVA and Post-hoc Analysis Results of Active Session Day

Baseline and Post-tDCS Session

Tukeys's HSD test shows that a statistically significant difference in performance exists between baseline (Mean time= 30.927 seconds) and post-tDCS sessions (Mean time= 25.869 seconds) with p=0.002 (p<0.05).

Active Session and Post-tDCS Session

Tukeys's HSD test shows that there is no significant difference in performance between Active (Mean time= 26.015 seconds) and post-tDCS sessions (Mean time= 25.869 seconds) with p=0.9935 (p>0.05).

Deduction

Results show that during the tDCS session, performance of the subjects was increased considerably as compared to baseline session. However, there was no further improvement and subjects maintained their performance across the third session (i.e. post-tDCS session) which is also evident from the mean time value of the two sessions (active session mean time=26.015 seconds and post-tDCS session mean time=25.869 seconds).

8.2 Results of Repeated Measures ANOVA with Sham tDCS

8.2.1 Normality Tests

Box and whisker plot showed that there are no outliers in the data.

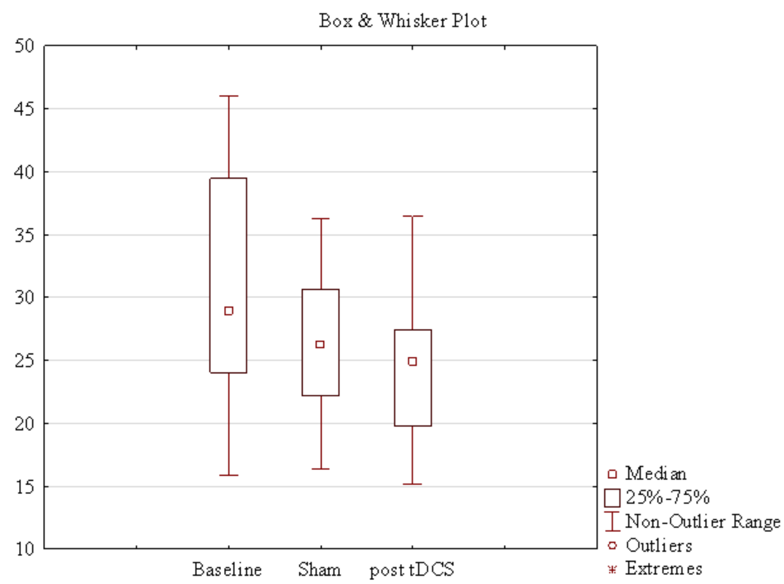


Figure 20 Box and Whisker Plot of Baseline, Sham, Post-tDCS session on day of Sham Session

8.2.2 Normality Plot of Baseline of Sham Group

P value=0.29 of Shapiro-Wilk's test shows that the data is normal (p>0.05).

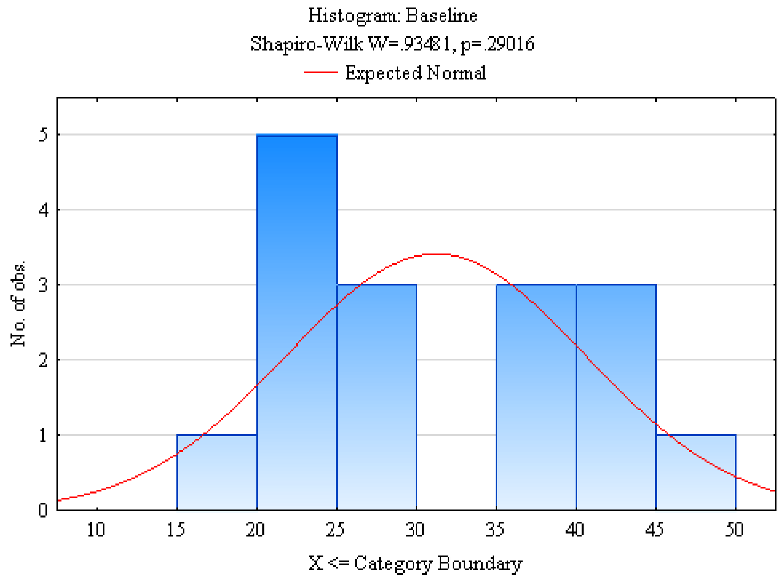


Figure 21 Normality Plot of Baseline of Sham Group

8.2.3 Normality Plot of Sham tDCS Session

P value=0.496 of Shapiro-Wilk's test shows that the data is normal (p>0.05).

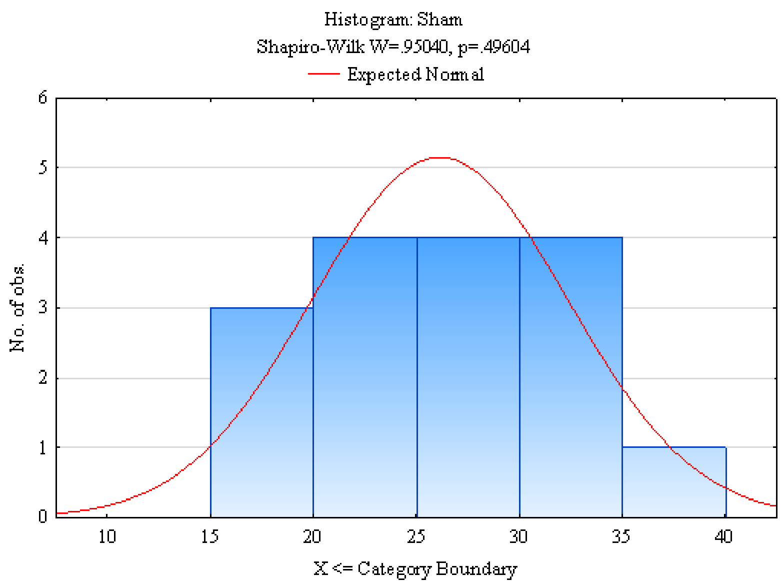


Figure 22 Normality Plot of Sham tDCS Session

8.2.4 Normality Plot of post-tDCS Session of Sham Group

P value=0.4357 of Shapiro-Wilk's test shows that the data is normal (p>0.05).

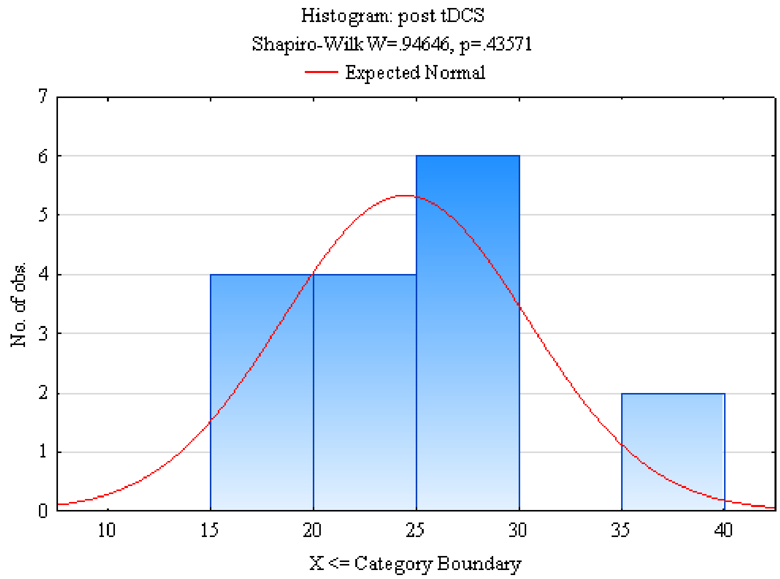
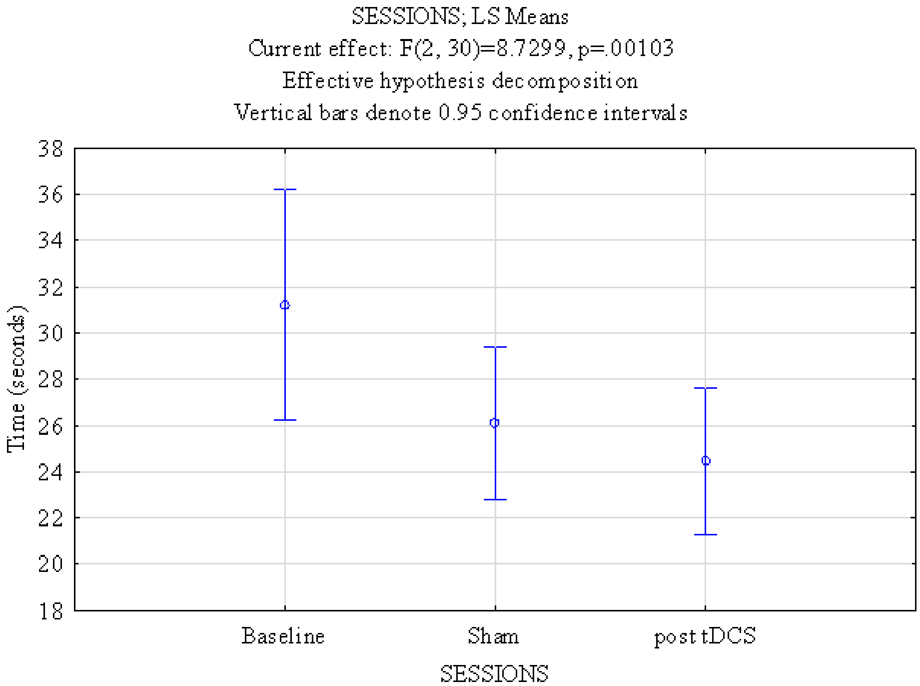


Figure 23 Normality Plot of post-tDCS Session of Sham Group

8.2.5 Post-hoc Analysis Results

Repeated measures ANOVA comparison between baseline, sham tDCS and post-tDCS resulted in in F(2,30)=8.7299 and p=0.001 (p<0.05) which shows that a significant difference in performance exists across the three sessions (Figure). To evaluate that which two groups differ from each other, post-hoc analysis was performed using Tukey's HSD test. Results of Tukey's test comparison are given below.



Cell No.	SESSIONS; LS Means (sham_new.sta) Current effect: F(2, 30)=8.7299, p=.00103 Effective hypothesis decomposition					
	SESSIONS	DV_1 Mean	DV_1 Std.Err.	DV_1 -95.00%	DV_1 +95.00%	N
1	Baseline	31.21740	2.333645	26.24335	36.19145	16
2	Sham	26.12771	1.548833	22.82645	29.42897	16
3	post tDCS	24.46006	1.494559	21.27448	27.64564	16

Cell No.	Tukey HSD test; variable DV_1 (sham_new.sta) Approximate Probabilities for Post Hoc Tests Error: Within MS = 22.710, df = 30.000			
	SESSIONS	{1} 31.217	{2} 26.128	{3} 24.460
1	Baseline			
2	Sham	0.013852		
3	post tDCS	0.001153	0.588960	

Figure 24 Repeated Measures ANOVA and Post-hoc Analysis Results of Sham Session Day

Baseline and Sham Session

Tukeys's HSD test shows that a statistically significant difference in performance exists between baseline (Mean time= 31.217 seconds) and sham tDCS sessions (Mean time= 26.128 seconds) with p=0.01 (p<0.05).

Baseline and Post-tDCS Session

Tukeys's HSD test shows that a statistically significant difference in performance exists between baseline (Mean time= 31.217 seconds) and post-tDCS sessions (Mean time= 24.46 seconds) with p=0.001 (p<0.05).

Sham Session and Post-tDCS Session

Tukeys's HSD test shows that there is no significant difference in performance between sham (Mean time= 26.128 seconds) and post-tDCS sessions (Mean time= 24.46 seconds) with $p=0.5889$ ($p>0.05$).

Deduction

The above results show that during the sham session, performance of the subjects was increased considerably as compared to baseline session. However, there was no further improvement and subjects maintained their performance across the third session (i.e. post-tDCS session) which is also evident from the mean time value of the two sessions (sham session mean time=26.128 seconds and post-tDCS session mean time=24.46 seconds).

PART IV

DISCUSSION
&
CONCLUSION

9 Discussion

9.1 Summary

The main objective of study was to evaluate the effect of transcranial direct current stimulation (tDCS) on acquisition of a novel motor skill, which in this case was laparoscopic surgical skill. The task was a bead placement task, which was performed with the help of a laparoscope. To evaluate the improvement in the task performance, a digital trainer was designed. The trainer was designed by using photo-reflective sensor to detect the presence of a bead. It was used to note the time of bead placement with a resolution of 1 ms. A double-blind crossover experiment setup was designed for tDCS that composed of two sessions over two visits separated by a washout period of 48 hours. 16 participants, naïve to the task, were recruited for the experiment and randomly assigned to any of the two intervention order. Subjects performed the task in baseline, tDCS and post-tDCS sessions. A significant performance improvement was observed in case of both active tDCS session and sham tDCS session as compared to their respective baseline with p=0.002 and p=0.01 respectively. No significant difference in performance was observed between stimulation sessions and post stimulation session and both had nearly identical performance.

9.2 Previous Work Comparison

Various studies have previously shown a positive effect of anodal tDCS on a number of moto learning tasks. tDCS not only improves motor learning in early stages of learning but also helps in retention [59-61].

This double-blind crossover study suggests that laparoscopic peg transfer skill can be improved by the application of tDCS. Subjects performed significantly better when given tDCS then no tDCS. Active tDCS resulted in p=0.002 whereas sham tDCS resulted in p=0.01. Though p value of active tDCS is considerably stronger than sham however there mean scores are not so different from each other. Active session has a mean bead placement time of 26.015 seconds whereas sham session has 26.128 seconds, which leads to the suggestion that the improvement in performance can also simply be because of practice. However, post-tDCS session after both active and sham stimulations had mean bead placement times of 25.869 seconds and 24.46 seconds respectively. This shows that performance improvement was limited only to the tDCS session. So performance improvement in tDCS session is not simply practice and tDCS must have played some part in it.

Some of the recent studies carried out on laparoscopic peg transfer task have shown no significant effect of tDCS on laparoscopic peg transfer tasks despite being significantly useful for other surgical tasks [70, 71]. The task used in our study was slightly different with the addition of a digital trainer. Moreover, our study used crossover study design in comparison to others mentioned above, which used parallel design. Our study was composed of two-day session separated by a washout period of 24 hours. No previous laparoscopic studies have yet been carried out that employed multiple tDCS sessions and a crossover study design.

Despite having contradictory results to similar laparoscopic studies, our study supports the results of a number of studies that suggests that tDCS can be successfully used to enhance the performance of a motor task [60, 61, 72]. However, it also suggests that difference in tDCS protocol can produce significant effects on results.

9.3 Choice of Study Design

This study is a double-blinded crossover study in which each subject goes through every kind of treatment in different periods. Double-blindness helps avoiding any kind of bias introduced by both the participant and the researcher. Crossover study helps significantly reduce the number of subjects as each subject serves his/her own control. Subjects are counter-balanced in each treatment order (equally divided in random order) to remove the bias of getting a particular treatment first. Subject were called on two separate days with a washout period of 24 hours to avoid any carryover effects.

9.4 Limitations

There are a number of reasons that this study might have task specific results. The task designed was modified from a standard laparoscopic peg transfer task due to involvement of a digital trainer. The trainer provides possibilities of countless new patterns and tasks. Mainly dominant hand was used in task performance and there was minimal involvement of non-dominant hand that is different from a standard bimanual peg transfer task. Task was approximately 1 hour and 15 minutes long. If a person is impatient or has some other task on their mind then it could also play a role in performance decline. Convincing subjects for two sessions and a long session including a tDCS is also quite difficult.

10 Conclusion

This study suggests that tDCS may play a role in performance enhancement of a peg transfer task when applied over M1 region contralateral to dominant hand however the results may be task specific to the type of task used in the study.

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PART IV

APPENDIX

APPENDIX A

11 Methods tested for Object Detection

Various techniques are available for object detection. Some of them were tested to assess the feasibility. A brief overview of tested techniques and their draw backs is given below.

11.1 Light-Dependent Resistor (LDR) Based Object Detection

LDR is a light dependent resistor that varies its resistance based on the intensity of light. LDR's were arranged at equal distances covered in an opaque cylinder to restrict detection angle to as close to 90 degrees as possible. The bead was supposed to be placed on top of cylindrical housing that was wrapped around LDR (Figure). Lightning was provided from three directions to avoid any shadow formation and increase the LDR sensitivity.

Figure 25 LDR Based Bead Placement Setup

The idea was rejected based on preliminary testing for following reasons:

1. Sensitivity was very low in the absence of light and very high in the presence of light
2. Shadows were causing LDR's switching
3. Unstable resistance values – were taking long time to settle
4. Locally available LDR's were of unknown values

11.2 Switch Based Detection (Make/Break)

Metallic beads were proposed to be used as a mean of contact formation and switching. Different techniques, which are given below, were tested in order to determine the feasibility of the idea.

11.2.1 Copper Plate/ Copper Mesh Based Detection

Copper plate and copper mesh both were tested as a housing for bead placement. A simple potential divider circuit was used to determine the established contact between metallic bead and copper plate or mesh.

The idea was rejected because there was no certainty of contact establishment.

11.2.2 R-2R Ladder Circuit

R-2R ladder circuit is a digital to analog converter with weighted resistors where each weighted resistor represents a bit. It is efficient as compared to simple potential divider as only two resistor values are used. Weighted resistors were used as switches that represented a bead position.

The idea was rejected mainly because of uncertainty of metallic bead connection. In addition to that, Arduino's ADC is 10 bits and total number of bead positions required in single row were 12. In order to compensate the two remaining positions the complexity of design was considerably high and inefficient.

11.2.3 Keypad Matrix Based Detection

Keypad matrix idea was proposed, as it was more precise for detecting exact location of placed bead. Keypad matrix is a row and column based design. A switch acts as a mean of connecting rows and column that pass over each other. The point where a row and column pass over each other represent a bead position. A metallic bead was used for switching.

Keypad matrix has limitations like masking and ghosting due to which the idea was rejected.

11.2.4 Magnetic Sensor Based Detection

Two different magnetic sensors (Hall Effect and Reed Switch) were tested. Both sensors had same working principle. Output Voltage of sensors vary in response to change in the magnetic field. So magnetic beads were required for detection in this design.

The idea was rejected after testing based on following reasons:

1. Sensors needed to be mounted in a particular orientation.
2. Sensors detected only magnetic objects.
3. The detection range of sensors was quite low and fixed.
4. No information of magnetic strength was provided of the magnets locally available.

11.2.5 Image Processing

MATLAB was used for the analysis and webcam was used for image acquisition. Images obtained were converted to black and white using thresholding in matlab. A dark spot represented the presence of a bead.

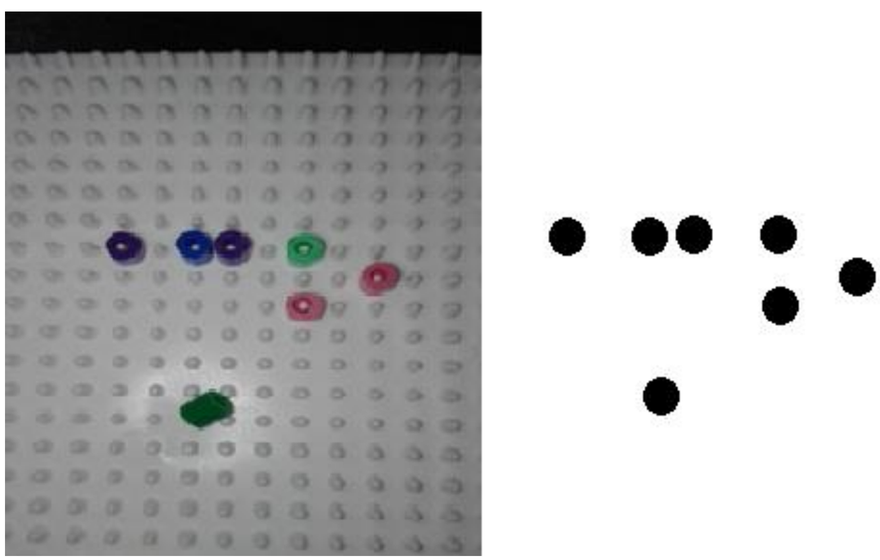

Figure 26 Black and White Thresholding Results

The idea was rejected due to following reasons:

1. Problems because of shadow formation while bead placement.
2. Problems in real time acquisition and timing accuracy while using MATLAB.
3. Not feasible for a portable system.

APPENDIX B

12 Circuits Schematics and Layouts

12.1 Multiplexer Boards Schematics

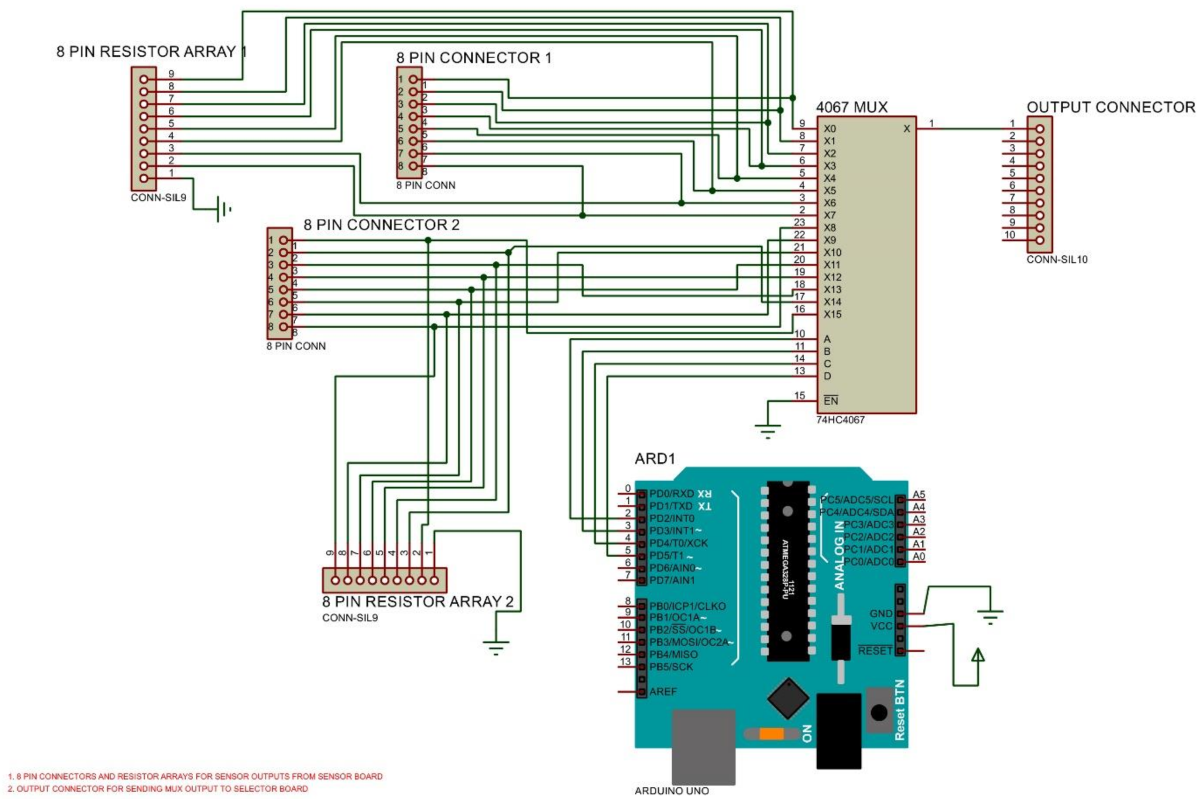

Figure 27 Multiplexer Board Schematics (Output of Each of 9 Mux Board Connects to Separate Pin in Output Connector. See Section 6.2.2)

12.2 Mux-Selector Board Schematics

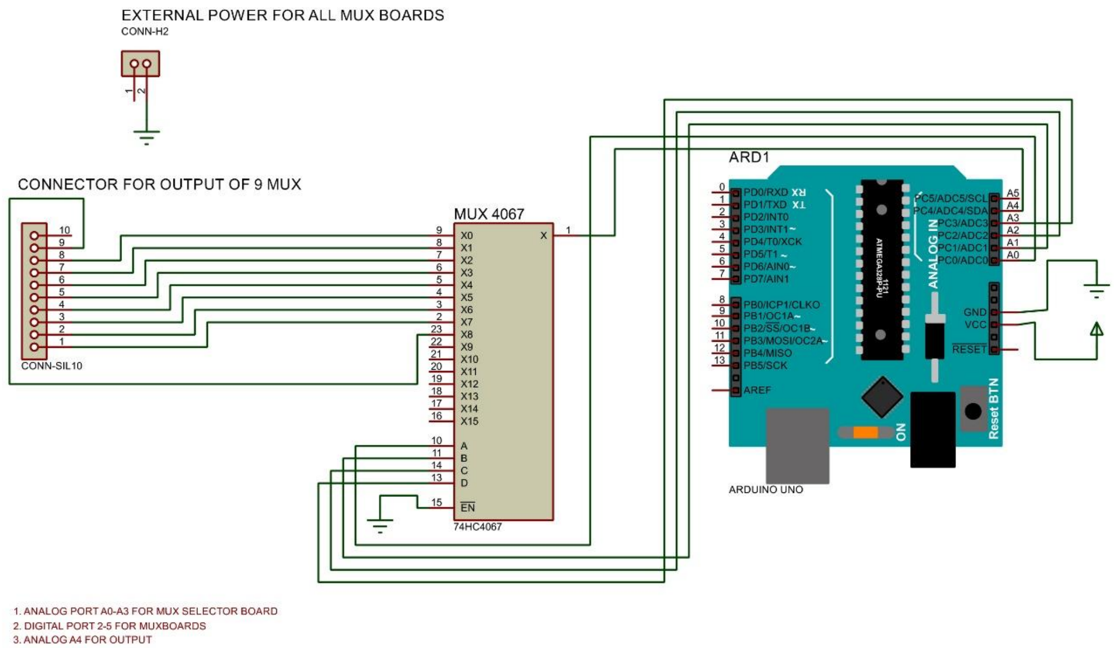

Figure 28 Mux Selector Board Schematics (For Power Specifications See Section 6.2.5)

12.3 Sensor Board Schematics

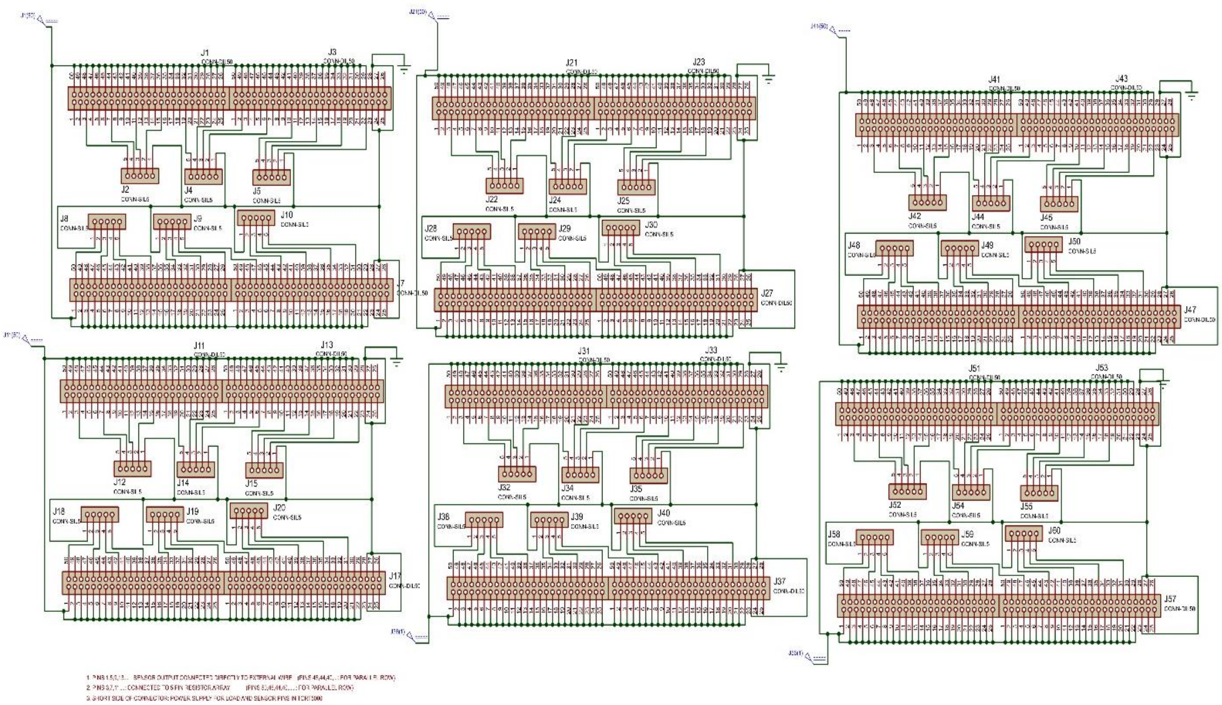

Figure 29 Sensor Board Schematics of 12 Sensor Rows (See Section 6.2.1)

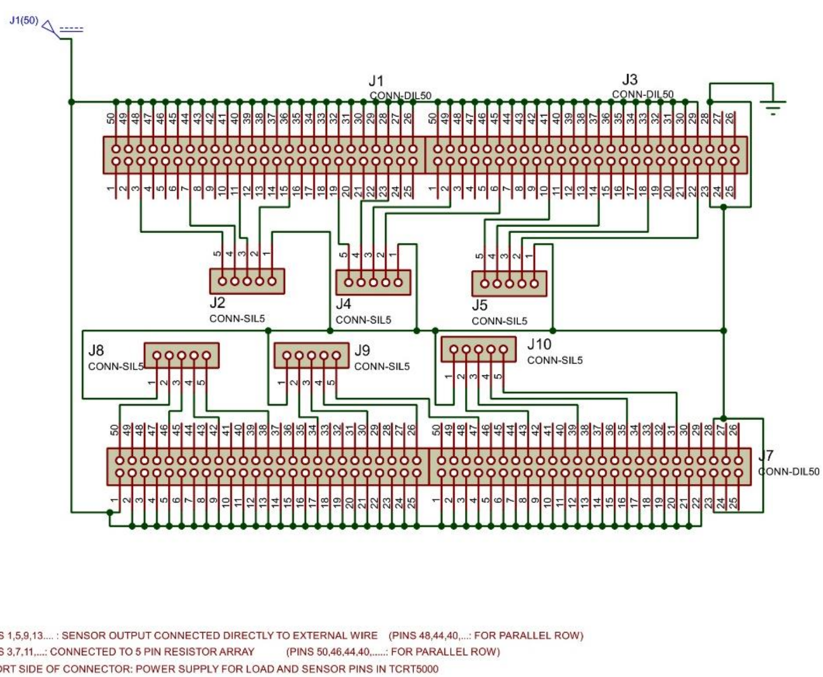

Figure 30 Two Rows from figure 29 Schematics (Rest of Design is Replication of this Configuration)

12.4 Subject Board Dimensions

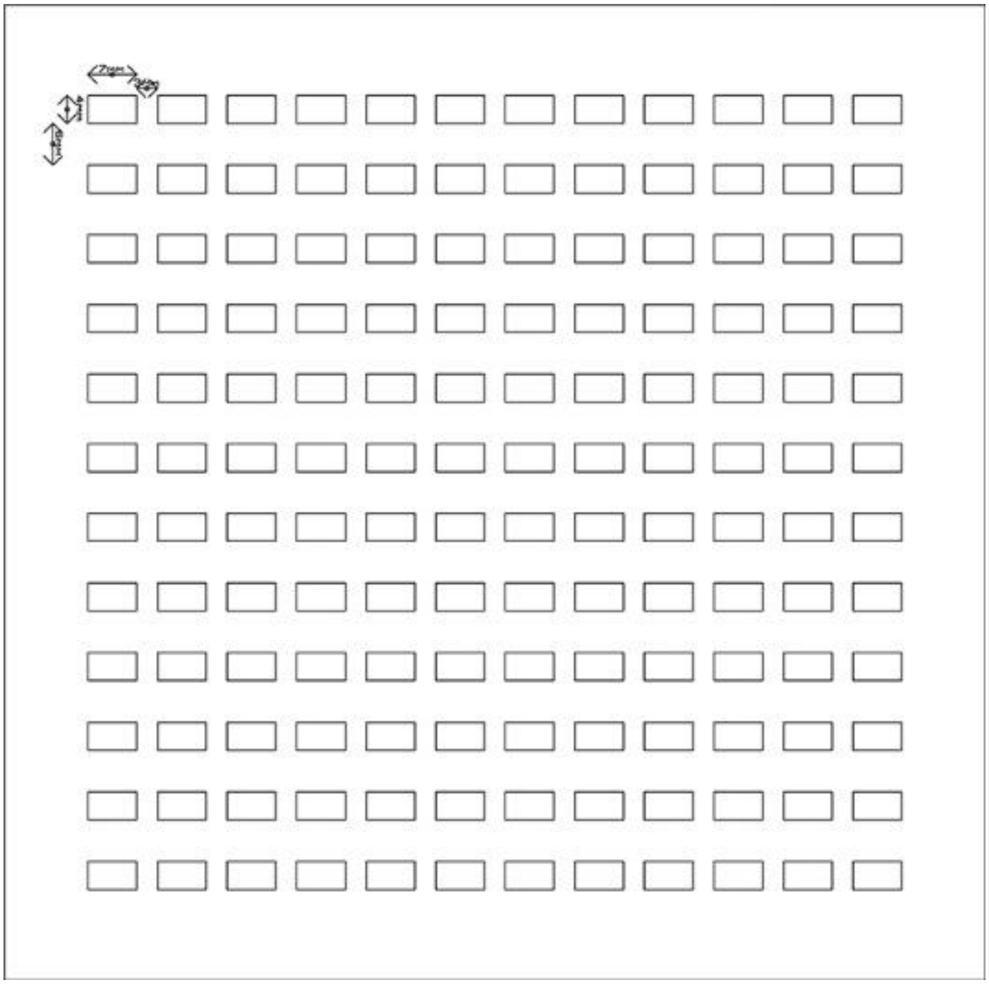

Figure 31 Subject Board Dimensions and Layout