Development and Validation of a Miniature Programmable tDCS Device

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***Abstract*—Research is being conducted on the use of transcranial direct current stimulation (tDCS) for therapeutic effects, and also on the mechanisms through which such therapeutic effects are mediated. A bottleneck in the progress of the research has been the large size of the existing tDCS systems which prevents subjects from performing their daily activities. To help research into the principles, mechanisms, and benefits of tDCS, reduction of size and weight, improvement in simplicity and user friendliness, portability, and programmability of tDCS systems are vital. This paper presents a design for a low-cost, light-weight, programmable, and portable tDCS device. The device is head-mountable and can be concealed in a hat and worn on the head by the subject while receiving the stimulation. The strength of the direct current stimulation can be selected through a simple user interface. The device is constructed and its performance evaluated through bench and *in vivo* tests. The tests validated the operation of the device in inducing neuromodulatory changes in primary motor cortex, M1, through measuring excitability of dominant M1 of resting right first dorsal interosseus muscle by transcranial magnetic stimulation induced motor evoked potentials. It was observed that the tDCS device induced comparable neuromodulatory effects in M1 as the existing bulky tDCS systems.**

***Index Terms*—Device, light weight, low power, miniature, portable, programmable, transcranial direct current stimulation (tDCS).**

I. Introduction

TRANSCRANIAL direct current stimulation (tDCS) is a noninvasive brain stimulation technique which applies constant low-intensity direct electrical current to the target brain region through two surface electrodes [1], [2]. The effect of tDCS is polarity dependent. Anodal tDCS, application of anode over the target treatment area, increases cortical excitability, while cathodal tDCS, application of cathode over the target treatment area, decreases cortical excitability of the applied area [3]. tDCS has demonstrated some therapeutic benefits [4] in alleviating and controlling pain, tinnitus, psychiatric diseases, depression, addiction, schizophrenia, anxiety disorders, dementia, and enhancement of attention, learning, and memory.

In recent years, apart from the use of tDCS systems for therapeutic benefits, extensive research is also being carried out to investigate the principles of tDCS and the mechanisms through which its therapeutic effects are mediated. However, a bottleneck in the use of the tDCS systems for therapeutic purposes, and in establishing their therapeutic mechanisms and benefits, has been the unavailability of reliable, low-cost, programmable, and portable tDCS devices that enable short-term and long-term brain stimulation under varying conditions and in different setups. As a result, there still remain some gaps in the experimental data investigating the mechanisms and benefits of the tDCS action.

Most of the existing tDCS systems utilise complex circuitry and are therefore bulky. These systems are connected to the electrodes via long lead wires that run from the stimulator to the subject's head. In order to simplify the use of tDCS systems for therapeutic benefits, reduction in size and weight, portability, and programmability of the tDCS systems would be essential.

This paper presents a novel design for a low-cost, light-weight, programmable, and portable tDCS device. The device is head-mountable and can be concealed in a hat and worn on the head by the subject while receiving the stimulation. The strength of the direct current stimulation can be selected through a simple user interface. The device is constructed and its performance evaluated in terms of its functionality through two bench and *in vivo* tests.

II. Existing Portable tDCS Devices

A study on the relevant literature indicates that thus far only several portable tDCS devices have been reported majority of which being commercial devices. These devices include but are not limited to: Magstim (U.K.), Rogue Resolutions Neuroconn (Germany), Soterix Medical (USA), GoFlow, Foc.us (USA), and The Brain Stimulator (USA). A comparison of these tDCS devices is presented in Table I. Although these tDCS devices share similarities in terms of their components and functions, they also have differences in terms of their circuit design, as well as internal and external features they offer. The stimulator by Rogue Resolutions is capable of adjusting currents of more than 2 mA and can generate up to 5 mA with increments of 0.25 mA. The published studies on tDCS recommend not to apply currents greater than 2 mA for treatment purposes, except for

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TABLE I
COMPARISON OF SIX EXISTING PORTABLE TDCS DEVICES

Device	Current Ranges	Electrodes	Power Source	Additional Features
Magstim (UK)	- Maximum current 2 mA per channel - Minimum 0.2 mA per channel - Current generation accuracy < 0.1 mA	- Sponge electrodes	- 2 batteries - Type AA/LR6 - 1.5V- KAA.	- Portable programmable DC stimulator - Mono-channel, Bi-channel and Sham stimulation modes - Maximum output voltage 28 V DC per channel.
Rogue Resolutions -neuroConn (Germany)	- Adjustable current up to 5 mA in increments of 0.25 mA	- Sponge electrodes	- Rechargeable batteries - 6 hours stimulation time by using 1mA - 7 hour recharging	- 1 channel (anodal and cathodal stimulation) - Adjustable application time up to 30 min - 2 standard modes: single and pulse with fade in and fade out - External trigger input
Soterix Medical (US)	- Adjustable currents: 1, 1.5, 1.75, 2 mA.	- Sponge electrodes.	- 2, 9 V Alkaline batteries. - Battery life is 3 hours.	- Adjusts the duration of the stimulation (10, 20, 30, or 40 minutes) prior to the start of stimulation.
GoFlow	- Adjustable currents: 0.5, 1, 1.5, and 2 mA		- 12 V battery	
Foc.us (US)	- Current ranges between 0.8 mA and 2.0 mA (2 mA is for use with external electrodes only)	- Sponge electrodes	- 3.7 V battery, 150 mAh. - Lithium polymer type (model 041230)	- Automatic shut-off - Bluetooth 4.0 - External electrode support - Internal vibrating motor
The Brain Stimulator (US)	- Adjustable currents: 0.5, 1, 1.5, and 2 mA (+/- 0.1 mA error)	- Stick-on electrodes	- Battery life of approximately 175 hours of continuous usage	- An LED indicates whether the device is on or off - Approximately three feet of lead wire - An internal capacitor that filters out AC noise

use in scientific and research applications. In addition, 0.5 mA is the minimum current level that can be set for most of these devices.

In relation to the stimulation electrodes, sponge rubber pad electrodes are the preferable type used in the existing portable tDCS devices due to their desirable characteristics such as lower resistance in comparison with other electrode types such as stick-on electrodes. Depending on the electrode position on the head and the amount of humidity, a varying resistance appears on the path of the stimulation current delivered to the target region. If the resistance (sum of electrodes and stimulation region) is high enough (more than 5 kΩ), the desired level of stimulation current may not be delivered accurately [7]. The Soterix Medical and GoFlow devices employ higher battery voltages (18 and 12 V, respectively) to tackle this issue. Using higher battery voltages would help overcome the high path resistance so that the desired current level can be delivered to the target area reliably. On the other hand, utilizing lower battery voltages would enable the tDCS device be devised using simpler and cheaper circuitry and prevent the possibility of high voltage shocks. To keep the current constant, the GoFlow device for example, utilizes an LM334 current source chip. In addition, instead of a potentiometer for generating different current levels, it uses four specific resistors connected to a four-position switch. This mechanism enables manual selection of the stimulation current level from 0.5 to 2.0 mA.

Considering the characteristics of the current devices, further reduction in their power consumption, size, weight, cost, and maintenance steps will be beneficial.

III. PROPOSED PORTABLE TDCS DEVICE

The circuit diagram of the proposed tDCS device is shown in Fig. 1. The device comprises hardware and software components. The hardware component includes a low-power microcontroller, a constant current source, a digital potentiometer, a linear voltage regulator, an ON/OFF switch, two micro pushbuttons, an LED, resistors, capacitors, coin cell batteries, a battery holder, a two-way electrode header, two electrode wires, and two electrodes. The software component includes a program in C language implementing the operation of the device including generation and delivery of the desired direct current.

A. ATtiny 24A

The main element of the device is an Atmel ATtiny 24A microcontroller [5]. It is a high-performance pico-power 8-bit microcontroller featuring 2 KB flash program memory, 128B data SRAM, 128B EEPROM, 12 general purpose I/O lines, an 8-bit timer/counter, a 16-bit timer/counter, internal and external interrupts, an 8-channel 10-bit analog to digital converter (ADC), a programmable watchdog timer, an internal calibrated oscillator, and four power saving modes. It can operate with a voltage source within the range 1.8–5.5 V. It can reach throughputs close to 1 MIPS per MHz by executing instructions in a single clock cycle. Its program memory can be reprogrammed in-system through an SPI serial interface. The ATtiny 24A provides four software selectable power saving modes.

The microcontroller is supported with a suite of programs as well as system development tools such as C compiler, macro assembler, and program debugger/simulator. Atmel Studio is an integrated development platform for developing and debugging the Atmel microcontroller based applications.

A 100 nf capacitor is placed between the VCC and GND pins of the microcontroller to bypass undesired high-frequency signals to ground. The 16-bit Timer/Counter 1 unit of the ATtiny 24A is used to create the required stimulation waveform. It facilitates precise wave generation, event management, and signal timing measurement. The unit is programmed to work as a free running timer. It can be clocked internally, via a prescaler. In this work, it is set to clock internally with the frequency of 1 MHz. A double buffered output compare register is compared with the timer/counter value at all time. The result of the compare is then used by a waveform generator to generate a pulsewidth modulated or variable frequency output on an output compare pin. The output compare pin A (OC1A) of the timer/counter, which is available on Pin 7 of the microcontroller, is used to create the stimulation waveform.

The ATtiny 24A has an 8-channel 10-bit successive approximation ADC which can be used to measure the voltage at eight single-ended input pins. The single-ended voltage inputs are measured against 0 V (GND). In this work, VCC is used as reference voltage for the single-ended channels. The channel 0 input of the ADC (ADC0) which is available on Pin 13 of the microcontroller is connected to the device VCC to monitor the variations of the battery voltage and adjust the programming of the AD5290 digital potentiometer dynamically. The device VCC would vary due to the depletion of the batteries used as the power source. This will result in a change in the output resistance of AD5290 which is sensitive to the variations of its power supply. The change would be then compensated for in software ensuring an accurate output resistance. A voltage divider is used to convert the VCC voltage to a voltage level that is acceptable by the ADC0 input of the microcontroller.

The ATtiny 24A has a universal serial interface (USI) which provides the necessary hardware resources required for serial communications. Supported with a minimal control software, the USI allows high data rates. The USI provides a three-wire operation mode which is compliant to the serial peripheral interface (SPI) mode 0 and 1. Pin names used by this mode are: DI, DO, and USCK. On the other hand, the AD5290 digital potentiometer provides also a three-wire SPI-compatible serial interface module. Accordingly, to communicate with the AD5290, DO of the microcontroller is connected to SDI of the AD5290, and USCK is connected to CLK. The communications are carried out in one direction only where the ATtiny 24A is the transmitter and the AD5290 is the receiver. Bit 1 of Port B, which is available on Pin 3 of the microcontroller, is used as an output pin to control the chip select pin CS′ of the AD5290.

Bit 0 of Port B, which is available on Pin 2 of the microcontroller, is used as an output pin to control an LED through a 330 Ω resistor. Bit 2 of Port B, which is available on Pin 5 of the microcontroller, and Bit 7 of Port A, which is available on Pin 6 of the microcontroller, are used as input pins driven by two micro pushbuttons. The internal pull-up resistors are activated for these two pins to support the operation of the pushbuttons.

B. AD5290

The AD5290 [6] is a high voltage, high performance, and compact programmable digital potentiometers. It can be utilized as a variable resistor or a resistor divider. The chip is available in 10, 50, and 100 kΩ output range options, while a 10-kΩ AD5290 is used in this work. The chip has three output Terminals A, B, and Wiper (W). The nominal resistance between Terminal A and Terminal B, $\mathrm{R_{AB}}$, is 10 kΩ with ±30% tolerance. There are 256 tap points accessed by Terminal W. The 8-bit data is programmed into an internal latch and then decoded to select one of the 256 possible settings.

The AD5290 is programmed to operate as a variable resistor where only two output terminals are used as a variable resistor (W and A, or W and B). The unused terminal can be floating or tied to the W terminal. We have used Terminals W and A, and Terminal B is floating. The resistance RWA between Terminals W and A starts at the maximum resistance value and decreases as the data loaded into the latch increases as follows [6]:

$$R_{\mathrm{WA}}\left(D\right) = \frac{256 - D}{256} \times R_{\mathrm{AB}} + 3 \times R_{\mathrm{W}} \qquad (1)$$

where D is the 8-bit data programmed into the latch, $\mathrm{R_{AB}} = 10\ \mathrm{k}\Omega$, and $\mathrm{R_W} = 50\ \Omega$. The variable resistance $\mathrm{R_{WA}}$ is used to vary the external resistance of the current source chip allowing for its output current to varied according to the requirement of the application in hand.

C. PSSI2021

The PSSI2021 [7] is a constant current source with stabilized output current of between 15 and 50 mA. The output current can be adjusted by connecting an external resistor $\mathrm{R_{ext}}$ to the chip as follows:

$$I_{\mathrm{out}} = \frac{0.617}{R_{\mathrm{ext}}} + 15\ \mu\mathrm{A}. \qquad (2)$$

Without an external resistor, the output current will be typically 15 μA.

A fixed 6.8 kΩ is attached to the PSSI2021. This resistor is connected to the programmable output resistance $\mathrm{R_{WA}}$ of the AD5290. By programming the AD5290's latch with an 8-bit data, the PSSI2021 can be therefore made to produce output currents within the range 200 μA and 2 mA in 200 μA increments.

D. MIC5209

The MIC5209 [8] is a linear voltage regulator with low dropout voltage at light loads and voltage accuracy better than 1% output. It provides low ground current to help extend the battery lifetime. The key features of the regulator include reversed-battery protection, current limiting, over-temperature shutdown, ultra-low-noise capability, and availability in thermally efficient packaging. It is available in adjustable or fixed output voltages. In this work, a fixed output voltage MIC5209-3.3 with an output voltage of 3.3 V is employed. The input voltage of the chip can vary within the range 2.5 to 16 V. It provides an output current of up to 500 mA. An external bypass 100 nF capacitor is placed between IN and GND, and a 1-μF capacitor is placed between OUT and GND to prevent oscillation. The MIC5209 is used to convert the 12 V input voltage to 3.3 V for powering the ATtiny 24A.

E. Software

A program was developed in C language and uploaded into the program memory of the ATtiny 24A. The pseudo-code for the program is presented in Fig. 2.

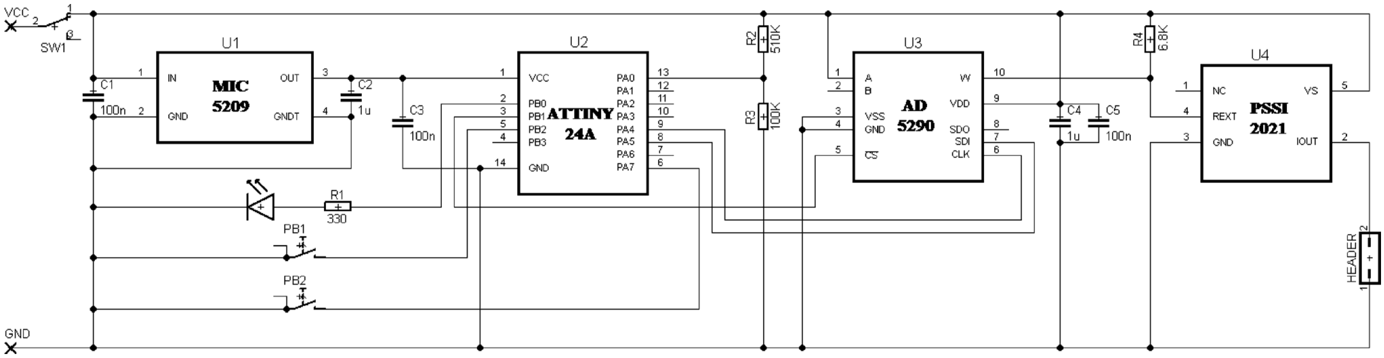

Fig. 1. Circuit diagram of the miniature tDCS device.

Begin

1. Set data direction for output port pins.
2. Initialize universal serial interface USI.
3. Initialize analog to digital converter ADC0.
4. Set Current to 200 μA.
5. Flash LED to indicate the start of the operation.
6. If Pushbutton 1 is pressed and Current < 2 mA, increase Current by 200 μA.
7. If Pushbutton 2 is pressed and Current > 200 μA, decrease Current by 200 μA.
8. Read battery voltage on ADC0, adjust Current if necessary.
9. If one minute is elapsed, Flash LED.
10. Go to 6.

End

Fig. 2. Pseudo-code for the program that operates the tDCS device.

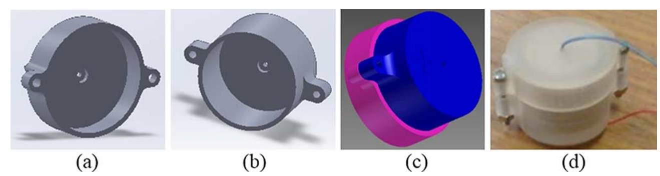

Fig. 3. Battery holder: (a) cover, (b) body, (c) cover and body together, and (d) 3-D printed.

In Step 1, data direction for output port pins is set. The two data direction registers DDRA and DDRB are initialized to set PA4 (USI's USCK) and PA5 (USI's DO) as well as PB0 (LED control) and PB2 (AD5290's CS′) pins as output pins. The other I/O pins are configured as input pins.

In Step 2, the USI Control Register USICR is initialized to enable USI and get it to operate in three-wire mode, positive edge clock source, software clock strobe, and toggle the USCK value.

In Step 3, the ADC is enabled by setting its ADMUX and ADCSRA registers. VCC is used as the required analog reference. Single ended input ADC0 is selected. We then write one into ADEN bit to enable the ADC. Also, to enable the conversion, one is written into ADC bit.

In Step 4, the digital potentiometer AD5290 is programmed through the USI to set the current to 200 μA.

In Step 5, the LED is continuously flashed to indicate the start of the device operation to the user, and also remind the user to select the desired current level using the pushbuttons.

In Step 6, Pushbutton 1 is read. If it is found pressed, and also if the output current is less than 2 mA, the output current is increased by 200 μA by commanding the digital potentiometer AD5290 through the USI.

In Step 7, Pushbutton 2 is read. If it is found pressed, and also if the output current is greater than 200 μA, the output current is decreased by 200 μA by commanding the digital potentiometer AD5290 through the USI.

In Step 8, the battery voltage is sampled on ADC0. The measured value is compared against a set of prespecified values associated with different battery voltage levels stored in a table. The best match is identified, and an 8-bit data for the digital potentiometer AD5290 for the best match is read from the table. The data is sent to the digital potentiometer AD5290 through the USI to ensure that the AD5290 is outputting the right resistance maintaining the output current of the tDCS device as close as possible to the desired level.

In Step 9, a free running timer is examined, and if it is found that one minute has elapsed, the LED is briefly flashed indicating to the user that the device is active.

In Step 10, a jump is taken to Step 6. Accordingly, the instructions in Steps 6–9 are iterated continuously ensuring the programmability of the device and that the desired current level is delivered to the target region of the brain.

F. Electrode

To deliver tDCS to the target brain region, two stimulation electrodes, named active and indifferent, are used. The electrodes are made of rubber carbon. They are embedded within a viscose bag that is made wet with saline solution. The electrodes are secured in the desired location on the head with a headband to prevent them from moving. A two-way header together with lead wires are used to connect the output of the tDCS device to the stimulation electrodes.

G. Battery

Four cell button lithium manganese dioxide CR2032 batteries of total nominal voltage of 12 V are used to supply power to the tDCS device for the duration of a stimulation action. The diameter and the height of each battery are 20 mm and 3.2 mm, respectively. The average weight of each battery is 2.8 g, and its rated capacity is 235 mAh.

H. Battery Holder

A 3-D battery holder is designed in SolidWorks to house the four cell button batteries. The designed battery holder is then printed using a 3-D printer. Fig. 3 shows the 3-D design involving body and cover, as well as the fabricated battery holder.

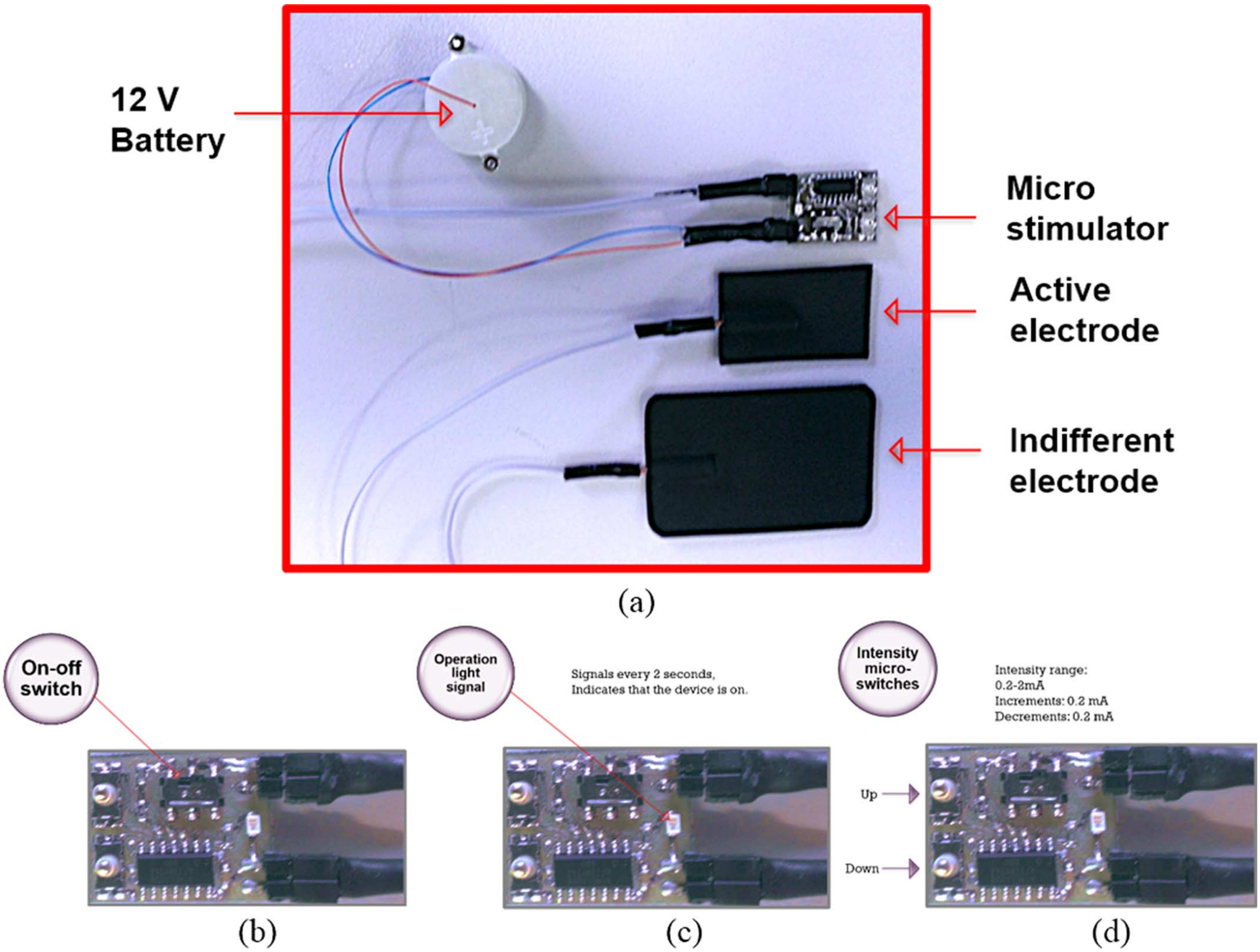

Fig. 4. (a) Complete tDCS device. (b) ON/OFF switch, (c) Operation light signal LED. (d) Current intensity selection micro pushbuttons.

I. Complete Device

A two-layer printed circuit board (PCB) of size 20×15 mm^2 is designed to host the components of the tDCS device. The board is milled using a PCB milling machine. The software is programmed into the ATtiny 24A microcontroller. The SMD electronic components are then soldered into the board. Fig. 4 shows the top and bottom layers of the board. The shape of the board is selected in a way to allow the board to be secured under a 20 mm coin-cell battery holder. All the components are mounted on the top layer. The batteries are placed into the battery holder. The ON–OFF switch is used to apply the power to the board. The two pushbuttons and the LED are used to implement the user interface. The micro pushbuttons are used to select the required output current intensity within the range 200 μA to 2 mA in 200 μA increments. Each press of the UP pushbutton increases the current intensity by 200 μA, while each press of the DOWN pushbutton decreases the current intensity by 200 μA. At the same time, the LED is flashed once for each 200 μA being sent out by the device. For example, if the output current is currently set as 1 mA, the pressing of the UP pushbutton makes the output current 1.2 mA and the LED is flashed six times to indicate the set current intensity to the user. The weight of the board is 1.65 g, the total weight of the four batteries is 11.32 g, and the overall weight of the device including the board, batteries, and battery holder is 18.27 g.

IV. Experimental Results

The tDCS device was constructed and its performance evaluated in terms of device functionality through two tests: bench and IN VIVO. The tests are described in the following.

A. Bench Test

In order to test the device, a 5-kΩ resistor that modeled the brain region resistance was connected to the two-way electrode header of the TDCS device. Four 235 mAh cell button batteries were inserted into the battery holder. During the continuous operation of the device, its steady state current consumption was monitored using a Keithley 2401 SourceMeter which can measure current in the range 10 pA – 1 A. The output current strength was varied within the range 200 μA to 2 mA in 200 μA increments in each hour. The current was then sampled using the SourceMeter every minute, and then stored in the SourceMeter memory. Finally, the current samples for each set current level

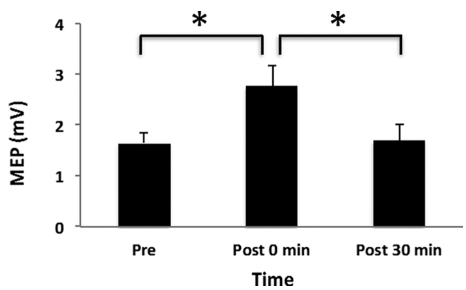

Fig. 5. Effects of anodal tDCS over M1 on the peak-to-peak amplitude of TMS induced MEPs over time. Stars indicate significant differences between different time points. Data is reported as mean$\pm$SEM.

were averaged. Overall, the device was found to produce current levels with around 93% accuracy.

B. *In Vivo Test*

The main objective of the *in vivo* test was to validate the efficacy of the device in inducing neuromodulatory changes in primary motor cortex (M1) in four healthy individuals. We hypothesized that the application of 10 minutes of anodal tDCS by this device increases M1 excitability, which lasts for at least 30 minutes. Four right-handed healthy participants (two men and two women) with a mean age of 32.7$\pm$ 4.3 years, received 10 min anodal tDCS (400 μA) in a pretest posttest design. Anodal tDCS was administered through an active saline-soaked surface sponge electrode (3×4 cm^2) over left M1 and a reference electrode (4×6 cm^2) over the right contralateral supraorbital area [9]. Excitability of dominant M1 of resting right first dorsal interosseus (FDI) muscle was measured by transcranial magnetic stimulation (TMS) induced motor evoked potentials (MEPs) using a commercial TMS system (Magstim 2002, Magstim Company Limited, Whiteland, Wales, U.K.). M1 excitability was assessed before, immediately, and 30 min after anodal tDCS. The result indicates that anodal tDCS of M1 increased M1 excitability immediately post intervention ($p < 0.05$). This increase returned to the baseline level after 30 min (see Fig. 5).

All participants tolerated the applied current very well. Slight tingling at the beginning of stimulation was reported by two participants.

C. *Discussions*

The proposed custom designed tDCS device induces comparable corticospinal excitability changes with similar side effects as those in the existing commercially available tDCS systems. Some of the authors had previously carried out similar studies on the effect of anodal tDCS on the brain excitability using a commercial tDCS system (Intelec Advanced Therapy System, Chattanooga, TN, USA). They had also used the same commercial TMS system (Magstim 2002, Magstim Company Limited, Whiteland, Wales, U.K.) to measure the brain excitability. The anodal tDCS outcomes produced by the developed tDCS device compared with those generated by the commercial tDCS system and verified by the commercial TMS system are in very close agreement (about 91%).

In the current practice, application of tDCS necessitates participation of an expert to locate the stimulation sites over the skull, fix surface electrodes over the skull, set the stimulation parameters on the device, and apply the stimulation current in an outpatient clinic setting. However, usually patients cannot afford to visit outpatient clinics frequently for receiving their prescribed daily tDCS therapeutic intervention. The developed device simplifies the application of tDCS and also enables the patients to self-administer tDCS at home. It also provides features such as low cost (less than \$5 per device), small size (board = 20×15 mm^2), low weight (board = 1.65 g; entire device = 18.27 g), low maintenance and ease of use, and simple battery replacement for unlimited stimulation. The small size and low weight of the developed device enable its placement in headgear such as a baseball cap (Fig. 6). Saline soaked pad electrodes are placed inside the cap at locations that correspond to the target cortical stimulation sites. To apply tDCS, the user sets the device to the desired current intensity and then wears the cap for the prescribed duration of stimulation.

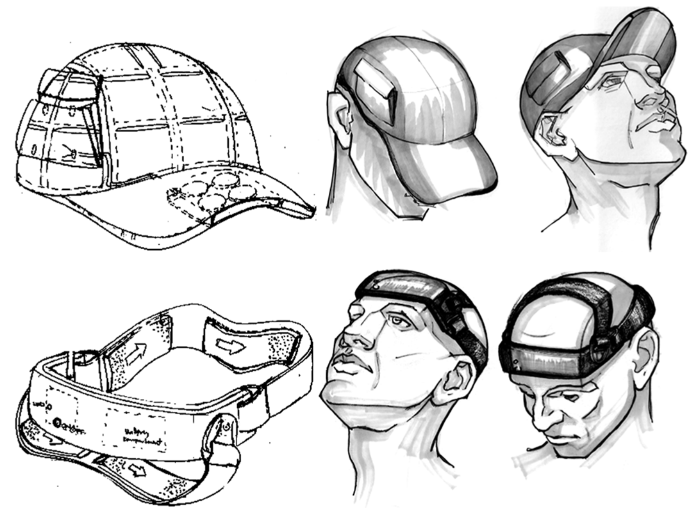

Fig. 6. Depiction of placement of the device in headgear to enable self-administration of tDCS by patients.

V. Conclusion

This paper presented design, implementation, and evaluation of a low-cost, light-weight, programmable, and portable tDCS device. The device is comprised of hardware and software components. The hardware component includes a low-power microcontroller, a constant current source, a digital potentiometer, a linear voltage regulator, etc. The software component includes a program that implements the operation of the device including generation and delivery of the desired direct current. The device was constructed on a printed circuit board, and its performance evaluated through bench and *in vivo* tests. The size of the board is 20 mm $\times$ 15 mm, and the weight of the board is 1.65 g. The overall weight the device including the board, four batteries, and battery holder is 18.27 g. The *in vivo* test validated the efficacy of the device in inducing neuromodulatory changes in M1 in four healthy individuals through measuring excitability of dominant M1 of resting right FDI muscle by TMS induced MEPs. It was observed that the tDCS device induced comparable neuromodulatory effects in M1 as the commercial bulky tDCS systems.

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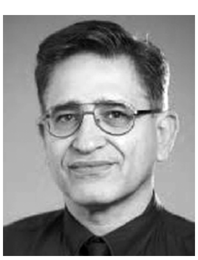

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