OPEN ACCESS

CLINICAL TRIAL Volume 14 (Issue I), 2025 | Page No. 23-35

Design And Evaluation of a Smart Electrotherapy Unit to Optimize Rehabilitation: A Clinical Trial

Adeena Zafar [1], *Muhammad Ebaad Khan* [1], *Muhammad Danish Mujib* [2*], *Hafsa Muhammad Arif* [1], *Wafa Hassan Khan* [1], *Muhammad Abul Hasan* [3]

[1]Student, NED University of Engineering and Technology, LEJ Campus, Karachi, Pakistan

[2] Assistant Professor, NED University of Engineering and Technology, LEJ Campus, Karachi, Pakistan

[3] Associate Professor, NED University of Engineering and Technology, LEJ Campus, Karachi, Pakistan

ABSTRACT

Background of the study: Stroke survivors are at high risk of paralysis, either in one form or another. In the following context, rehabilitation has been a practical domain to cater to the challenges and limitations faced by stroke individuals. To be precise, electrotherapy has proven to be a promising solution for pain and spasticity. This project aims to take an optimistic approach by integrating TENS and FES into a single system and, concurrently, designing a Bluetooth-controlled app to enable remote control of the device's modes and parameters.

Methodology: A battery powers the SET Unit and the user operates the device through a Bluetooth mobile app. The input is fed to the microcontroller that processes the input and sends control signals to the TENS or FES unit. The selected module generates electrical pulses delivered to the patient's body through electrodes placed at the specified area. Simultaneously, feedback is provided to and from the mobile app to adjust the parameters or send real-time updates of the therapy session.

Results: The results consisted of obtaining monophasic waves and controlling the pulse width modulation (PWM) and pulse amplitude within the range of 1-50 mA for TENS and 1-100 mA for FES. These parameters were successfully varied using a smartphone application.

Conclusion: Smart Electrotherapy Unit (SET) will bring innovation in rehabilitation and physiotherapy, providing an exhaustive solution to pain management and muscular movement.

Keywords: *Paralysis, rehabilitation, electrotherapy, remote control, functional electrical stimulation, transcutaneous electrical nerve stimulation.*

INTRODUCTION

For decades, peripheral nerve stimulation has been widely used to overcome medical disorders involving peripheral nerves, such as stroke and chronic pain. The peripheral nervous system performs all voluntary and involuntary actions. Thus, any sort of pain or difficulty during muscular movement is directed to the nerve tissue[1-3]. The mechanism of action is known to have been initiated in 1960, termed the Gate Control Theory proposed by Melzack and Wall. According tothis theory, the spinal cord acts as a" gate," allowing or blocking the pain signals from travelling to the brain.

***Corresponding Author:** Muhammad Danish Mujib

Email: danishmujib@neduet.edu.pk

Citation: Zafar A, Khan ME, Mujib MD, Arif HM, Khan WH, Hasan MA. Design and evaluation of a smart electrotherapy unit to optimize rehabilitation: a clinical trial. Pakistan Journal of Rehabilitation. 2025 Jan;14(1):23-35. https://doi.org//10.36283/pjr.zu.14.1/005

Received: Fri, June 14, 2024 **Accepted:** Mon, Dec 30, 2024 **Published:** Tue, Jan 7, 2025

At the spinal cord level, the pain sensation is detected by specialized nerve endings called "nociceptors," which are essentially sensory receptors that initiate the transmission of pain perception to the brain[3-5]. In the context of stroke-induced paralysis, electrotherapy has been a promising solution for pain and spasticity[6-8]. The term encompasses medical interventions for both central and peripheral nervous systems, inducing physiological responses in the nerves or tissues of the human body. This response is beneficial in providing pain relief, tissue repair, strengthening and restoring muscle movements, and improving the body's overall functioning[2]. Thus, for techniques like Transcutaneous ElectricalNerve Stimulation (TENS) and Functional Electrical Stimulation (FES), peripheral nerve stimulation distinguishes itself as the specialized modality in the modulation of peripheral nerves. Electrotherapy is a sub-technique that utilizes mild electric currents to regulate neural activity. Thus, the goal of designing a Smart Electrotherapy Unit (SET Unit) is to provide rehabilitation by integrating the two different electrotherapy interventions, including Transcutaneous Electrical Nerve Stimulation(TENS) and Functional Electrical Stimulation (FES), to assist individuals with stroke-inducedparalysis. The prototype uses electrical impulses to stimulate muscles and nerves for therapeutic purposes, along with the enhanced features of controlling with a mobile application. This allows users to customize their therapy sessions and progress at their own pace. Moreover, TENS is a battery-operated device that uses low-voltage electric currents to deliver electrical impulses via electrodes attached to or near the pain area at the skin's surface. It blocks the nerve fibres that carry pain signals to the brain. TENS is a cost-effective, non-pharmacological approach employed to address both acute and chronic pain condition [9-11].Similarly, FES is an assistive technology that stimulates muscles to restore muscular movements. It targets the efferent nerve fibres or motor nerves that transmit the electrical impulses directly from the CNS to the target muscle to contract or cause movement. Moreover, the motor nerves control voluntary and involuntary movements as well. This technology has been immensely beneficial, especially for restoring movement after paralysis. Electrical discharges stimulate muscle contractions for tasks including gripping keys, holding toothbrushes, standing, and walking[12]. The Smart Electrotherapy Unit is designed in different stages, including hardware design, Bluetooth-controlled app design, data collection and interpretation, and testing and validation. In the hardware process, the circuitry was designed and integrated into one to obtain the desired outputsignals. Moreover, for the software design, wehave used MIT App Inventor to design the Bluetooth-based application to smartly control the device, allowing the users to select the type of therapy and adjust different modes and parametersas per choice. Several types of research have been done in designing the TENS and FES unit, controlling through Arduino, and developing a mobile application. Moreover, previous studies related to peripheral nerve stimulation have also been done.A few of them are discussed below.

1. The first research was about a three-week PNS used to determine the effect on reducing chronic hemiplegic shoulder pain. Twenty-five participants in total, 13 treated with PNS and 12 with usual care. Percutaneous electrodes were given for PNS and outpatient PT by the therapist, along withexercises, for usual care. Shoulder discomfort decreased and lasted for more than 12 weeks post-treatment. Thus, a Three-week PNS is safe and effective[13].
2. This study observed the impact of TENS and FES on stroke patient's gait characteristics. Thirty stroke patients, 15 eachdivided into TENS and FES. TENS stimulates sensory nerves (sural nerve of the paretic limb), and FES is used for motornerves (below the fibular head in the paretic limb). Immediate improvement in speedis only possible in FES; thus, FES can restore walking ability faster[14].
3. A simple design and step-by-step transcutaneous electrical stimulator (TES) prototyping is presented. The stimulator contains three primary modules: aDC-DC boost converter, a Full H-bridge driver, and a Microcontroller unit. The stimulator is easy to use for non-invasive spinal cord stimulation. This could be beneficial for many communities globally. However, testing it in specific settings designed for TESCS will help understand how the stimulator influences the

nervous system[15].

4. Propose a TENS system that can relieve any patient's muscular pain and sprain using an electrical current. The dutycycle is controlled using the PIC18f4550 microcontroller. The user must select the mode from continuous or burst mode. Frequency, amplitude, and width in continuous mode can be adjusted using analogue input to ADC of PIC18F4550. Under the patient's control, the current gradually increases until tingling is felt.Symmetric waveforms with variable frequency (50-100Hz) were generated using the Timer module of PIC18F4550[16].

METHODOLOGY

The study design bench testing of the device is conducted to evaluate the operational performance of the SET Unit and ensure that it follows the safety protocols and is ready to be tested on human subjects. This will be followed by human trials, where several participants will test the device and provide real-time feedback, which will be used to further optimize the effectiveness of the SET Unit before introducing it to the market The study includes 20 healthy participants (10 males and ten females; 20-45 years) for initial trials. This sample size is sufficient to assess the SET Unit's functionality and user satisfaction while ensuring practical preliminary evaluation and data analysis. Moreover, participants provided informed consent and exhibited their willingness to participate in the study. Patients with implanted devices, such as pacemakers, and severe or open wounds at the electrode placement site were excluded from the trials. The study was conducted with the approval of the Research Ethics Committee, NED University of Engineering and Technology.

Figure 1 displays the experimental protocol of the study. The procedure was explained to all participants, who were instructed to sit and relax. Next, the participants were divided into two groups (Group A and Group B), comprising an equal number of participants in each group: 5 males and five females. The experiment began with a Cold Pressor Test (CPT) to measure the pain threshold. After experiencing 10 seconds of maximum pain CPT, the participant removed their hand from the cold water. CPT was performed twice: before and after the stimulation. Following the initial CPT test named CPT1, the participants rested for 30 minutes. Both groups then received 15 minutes of stimulation, with Group A using the Commercial TENS unit (Intensity Combo III, USA) and Group B using our developed SET Unit. After stimulation, both groups underwent a second CPT named CPT2.

Cold Pressor Test (CPT)

The Cold Pressor Test is used to study pain intensity and response by exposing the human body to frigid temperatures, typically around 1-4°C. The method induces nociceptive thermal pain and measures the pain threshold reported by each participant. The experiment began with the protocols mentioned in various studies[17,18,19]. Following this, all participants were instructed to submerge their leading hand up to their wrist in ice-cold water at a water temperature between 1°C and 4°C. The moment pain became unbearable for the participant, they withdrew their hand from the chilled water. Pain intensity was measured using the numerical pain intensity scale after 10 seconds of hand withdrawal from CPT.

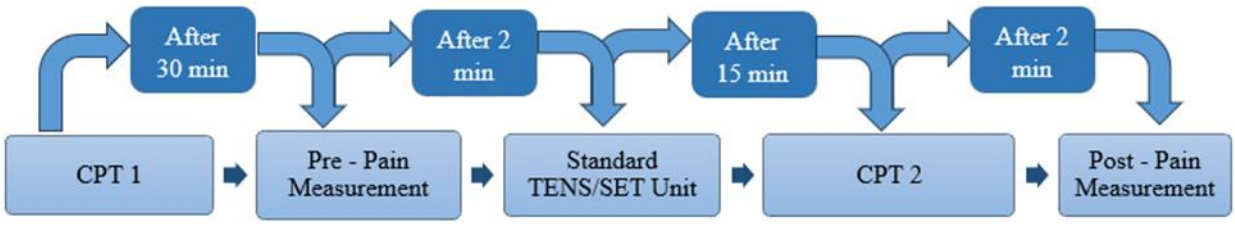


Figure 1. Experimental Protocol of the study

A. Development of Smart Electrotherapy Unit

Selection of Battery/ Power Supply

Selecting the correct battery for the SET unit is crucial for the device to work properly. The TENS and FES units mostly require a voltage range of 0-100 volts. The choice depends on the specifications and may vary from one device to another. Thus, we will use either a 9V rechargeable battery for our SET unit or another as needed.

User Interface and Control

A battery powers the SET Unit, and the user operates the device through a Bluetooth mobile app. The modes and parameters are customizable; for example, selecting TENS or FES mode and setting the pulse duration or intensity is entirely up to user preference.

The Control System

This input is fed to the control system, where the microcontroller processes the input and sends control signals to the TENS or FES unit. The selected module generates electrical pulses through a pulse generator such as a 555 timer IC. The pulse generator also controls the device's parameters, such as intensity or pulse frequency. These pulses are delivered to the patient's body through electrodes placed at the area of therapy needed. Simultaneously, feedback is provided to and from the mobile app to either adjust the parameters (the user inputs the command) or send real-time updates of the therapy session (through the microcontroller). Figure 2 displays the block diagram of the SET unit.

Software Bluetooth App Design

The hardware design was completed by designing a Bluetooth app using a Bluetooth module HC-05 to develop an interface controlled through the mobile app to allow the users to select their respective mode (TENS or FES) for using the device. Controlling the SET unit using the Bluetooth app is a novelty in our project. The MIT App Inventor is used to design the application, named 'SET_UNIT.'

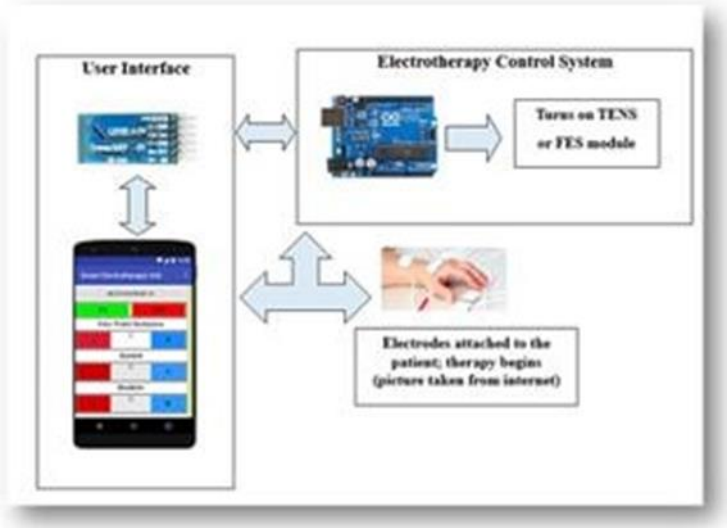


Figure 2. Block Diagram of SET Unit

System Architecture

The design consists of hardware and software design.

Hardware Design Key Components

The following components mentioned below were used in designing the SET unit. Figure 3 displays the component list.

1. **Arduino UNO**

Arduino is used for creating electronic projects. It consists of a microcontroller (programmed circuit panel) and Software that runs on the computer. This board comes with six inputs of analogue, 14 digital input or output (I/O) pins that can be used for PWM generation, a USB connector, and a reset button. The Arduino Uno replaces the PWM generator circuit in this work[20].

2. **MOSFET IRF9640**

The IRF9640 metal oxide semiconductor field effect transistor (MOSFET) is efficient enough to produce low power output. It is used for switching purposes and amplifies electronic signals. Signs. MOSFET is a three-terminal transistor consisting of a source, body, drain, and gate terminal. However, the body and source are internally short-circuited, making the transistor a three-terminal device[21].

3. **Potentiometer**

A potentiometer is used to regulate the output current that is injected into the human skin. It also changes the terminal voltage. Thus, the body's current flow can be adjusted to avoid discomfort[22].

4. **Resistors**

Resistors are used to limit the amount of current flowing through a circuit.

5. **Capacitors**

Capacitors are used to ensure smooth operation and minimize electrical interference. It also reduces the electrical hazards for patients and operators.

6. **Power Supply/battery 9V**

A 9V battery provides a compact and portable power source, making it suitable for our project to operate in remote locations without access to mains power.

7. **Step-up transformer**

A step-up transformer can provide the required voltage boost. In this circuit, the required voltage is 60V, with a 1:10 ratio of transformer[21].

B. Software Design Components

Bluetooth Module

The HC-05 module is a cost-effective and reliable solution for adding Bluetooth capabilities to various electronic devices and projects

.

MIT App Inventor

MIT app inventor is used to build an application to control an electrotherapy unit remotely through a smartphone via Bluetooth (HC-05 module). The design editor is a drag-and-drop interface that lays out the elements of the application user's interface. In contrast, the block editor in an environment in which the app inventor visually lays out to describe their app's logic using colour-coded blocks that snap together like puzzle pieces to describe the program[23].

Working

Using the mobile application, Arduino will receive the command to activate the TENS or FES circuit. The Arduino will direct the MOSFET (Metal Oxide Semiconductor Field Effect Transistor) to turn ON. The low-voltage current from the power supply (9V) will begin to flow. The present voltage is inconsistent/ fluctuating and needs to be stabilized. This is done in voltage regulation, where a capacitor (10-100 microfarad) smooths out the AC voltage. Next, the stable, low voltage

needs to increase. For this, a step-up transformer will increase the voltage to a higher or desired level.

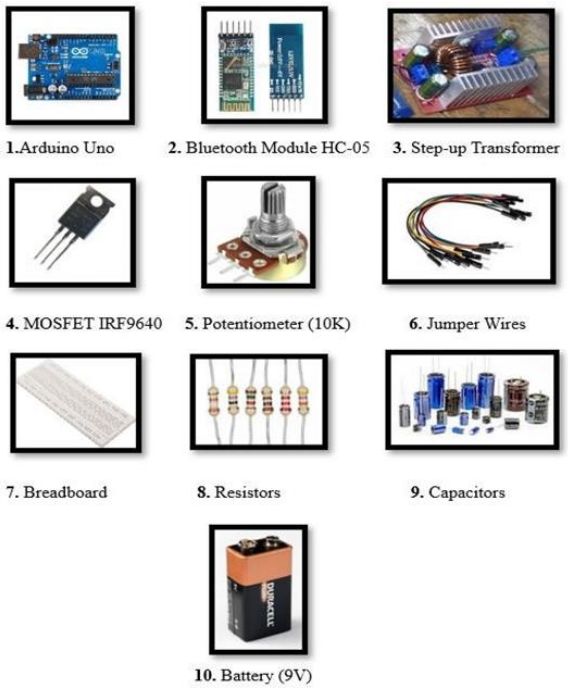
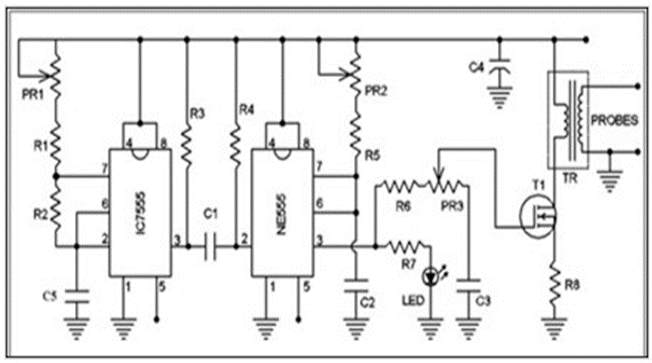


Figure 3. Components Used in the Design of the Prototype

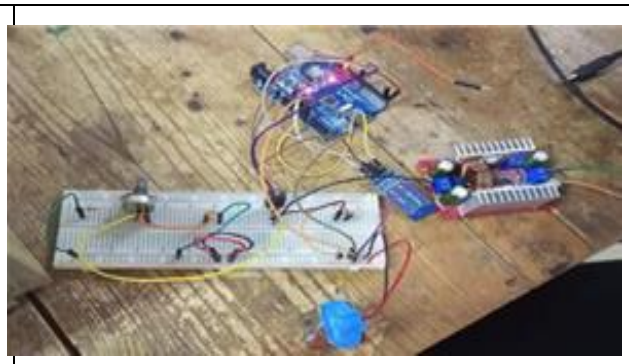
Prototype Design

The prototype is designed in two phases: Hardware (shown in Figures 4 (a, b and c) and Software (shown in Figures 7,8 and 9) Application.

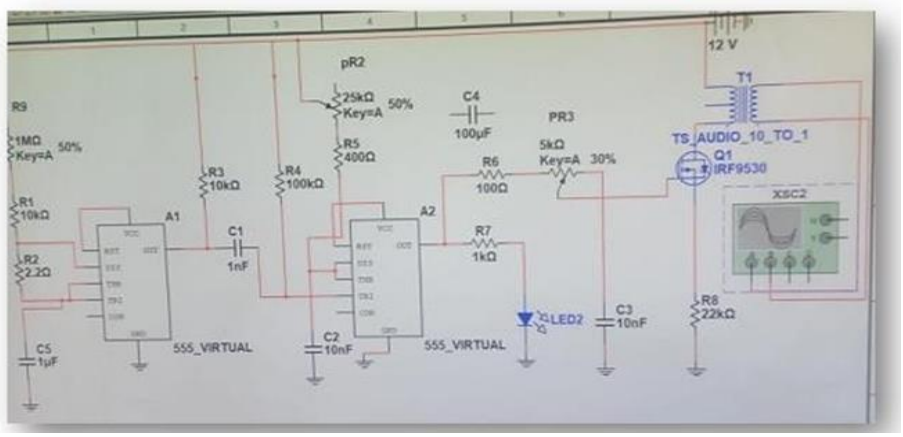
A. Circuit Diagram and Hardware implementation



a. ***Circuit Diagram of SET Unit***



b. ***Final Breadboard Circuit***



c. *Multisim Circuit*

Figure 3. a, b, and c show the final circuitry and representation of the SET Unit

A. Smartphone Application

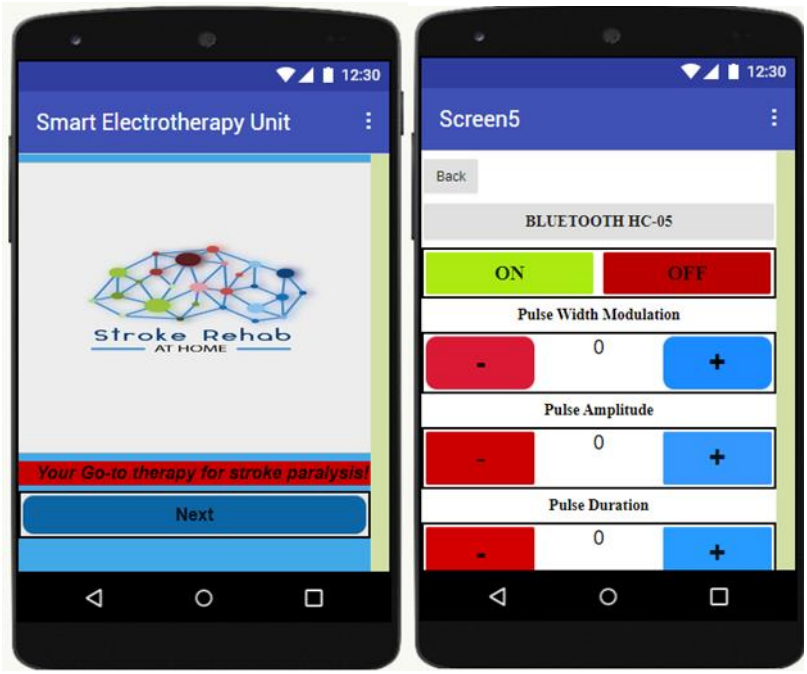


Figure 5. User Screen interface first & final screen

Figure 6. Coding Blocks of MIT App Inventor

RESULTS

A. Analysis of Experimental Procedure

The results from the experimental process are displayed in Table 1 below. The outcomes for pain perception for commercialized TENS and SET units were compared to determine their effectiveness using the visual analogue scale. The participants rate their pain levels on a numerical scale that is employed to evaluate the intensity of pain, ranging from 0 to 10, where mild or no pain lies on the left side of the scale closer to 0, and intolerable pain is rated at the right, close to 10. Analysis of demographic data revealed no statistically significant difference ($p > 0.05$) in age and pre-pain intensity across two groups (Group A: age =25.5 ± 2.31 years and pain intensity =7.7 ± 1.49) and (Group B: age = 25.2 ± 2.67 years and pain intensity = 7.5 ± 1.43). The post-pain intensity scores of Group A ($p = 0.0001$) and Group B ($p = 0.0012$) exhibited a significant difference compared to the pre-pain intensity scores of both groups

Cold Pressor Test Results (CPT)					
	GROUP A			GROUP B	
Subject	Pre-Pain Measurement Intensity	Post-Pain Measurement Intensity (After TENS Therapy)	**Subject**	Pre-Pain Measurement Intensity	Post-Pain Measurement Intensity (After Testing SET Unit)
1	8	6	**1**	7	4
2	9	6	**2**	9	6
3	8	5	**3**	5	2
4	7	4	**4**	7	3

5	6	3	**5**	8	5
6	9	5	**6**	6	2
7	5	2	**7**	9	5
8	7	3	**8**	8	5
9	8	5	**9**	6	2
10	9	6	**10**	5	2

Table 1. Results of the Experimental Procedure show changes in pain intensity levels of CPT before and after applying TENS and SET therapy. The pain intensity overall decreases after the treatment

Analysis of Parameters of Smart Electrotherapy Unit (SET Unit)

The results from the prototype are shown below (Figure 10). The Pulse Width Modulation (PWM) varied in the range 0-10, during which time the duty cycle changed from 9% to 99%. The voltage level was achieved at a maximum of 60 V after stepping up the voltage using a step-up transformer. We successfully achieved monophasic waves, like the standard research, as these pulses have an add-on advantage in allowing precise selection of muscles or nerves in stimulating and are relatively more straightforward to generate than other waves, such as biphasic waveforms. Moreover, our prototype's pulse amplitude (mA) is paramount. We have targeted the parameter within the range of 1-50 mA for TENS, which is acquired by 80% of TENS units; the range is safer and comfortable enough to provide pain relief and is below the motor threshold, the value at which we induce muscle activity. In contrast, 1-100 mA for the FES unit is targeted after a thorough study and keeping up with almost 80% of the research work. Arduino Uno, Bluetooth HC-05, LM324 IC, and MOSFET IRF9643 drive our circuit. According to Figure 9, the coded blocks display the working of the smartphone application. Considering the block of pulse amplitude, when the value is not equal to 0, we subtract the initial value from 1 to obtain the result. Similarly, when the value is not equal to 10, then we add 1 to it to acquire the final value. For instance, when the present number is four, and we need to decrease the pulse amplitude, the subtract button will be pressed, the coding block will read the value as not equal to 0, subtract one from it, and the result will be 1. The opposite is true for increasing the pulse amplitude**.**

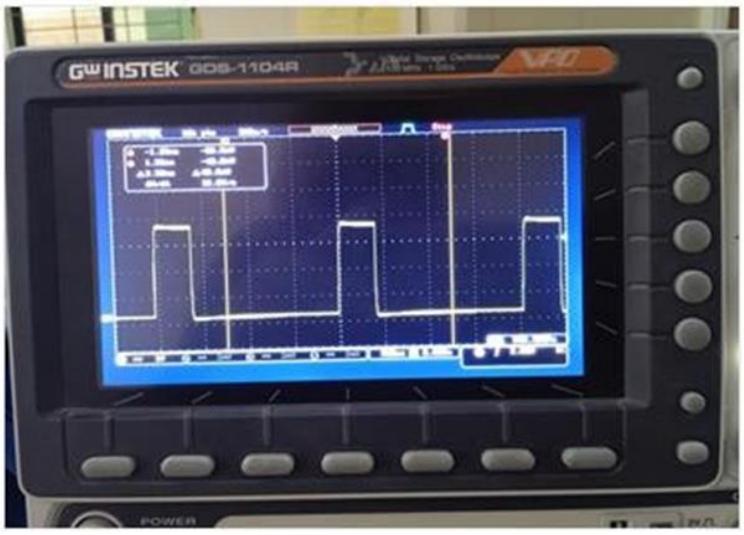


Figure 7.. Obtained Monophasic Waves

DISCUSSION

The Smart Electrotherapy Unit is designed under different stages, including hardware design, Bluetooth-controlled app design, data collection and interpretation, and testing and validation. In the hardware process, the circuitry was designed and integrated into one to obtain the desired output signals. Moreover, for the software design, we have used MIT App Inventor to design the Bluetooth-based application to smartly control the device, allowing the users to select the type of therapy and adjust different modes and parameters as per choice. The whole circuit is driven by

Arduino Uno, which acts as the main board to connect hardware with software applications. Furthermore, the circuit is designed to produce efficient therapy for stroke-induced paralyzed patients, which can be easily performed at home. This saves the time of visiting rehabilitation centers, leaving a burden of maintaining consistency by the patients and their caretakers. Thus, with the advent of technology, our design has vast applications in rehabilitation and medical devices[23,24,25]. The TENS unit works on the mechanism of Gate Control Theory. As a result of the electrical current activating nerve cells, the transmission of pain signals is disrupted, and your perception of pain is altered. Concurrently, it boosts the production of endorphins, the natural pain-killing chemicals produced by the body, activating the body's innate capacities to alleviate pain[4,26,27]. Moreover, Neuromuscular electrical stimulation is the core principle of FES unit. It involves delivering appropriate and regulated electric current via electrodes placed on the skin, stimulating the nerves that cause muscle contraction. This enhances muscle strength and restores functional movement, usually after paralysis[25,28,29,30]. Previous studies have shown to treat paralysis, such as chronic hemiplegia using TENS and improve motor function as well as provide comfortfrom excruciating pain[31]. Further, it was studiedthat applying TENS on a stroke patient's muscle ornerve belly significantly reduces spasticity[27]. Similarly, numerous studies have been done to determine the therapeutic benefits of FES, in cases such as ischemic or hemorrhagic stroke, where significant therapeutic effects were observed in patients[32]. Based on the research, our prototype effectively deals with stroke-related paralysis and demonstrates an innovative solution in providing acomparatively reliable and affordable device consisting of dual-mode therapy. The experimental results significantly strengthen our study by providing robust evidence of the effectiveness of our SET unit. The data demonstrate that the SET unit functions efficiently as a stimulation device, underscoring its potential for commercial application. We also compared our device with the benchmark and observed the standard and proposed parameter range, to validate the device. The subjects that received the therapy were satisfied and content with the smartphone control and adjustable scale. Our prototype is cost-effective and user-friendly as compared to alreadyexisting market devices. The TENS and FES units are expensive and available as separate devices[33,34].The SET unit can be utilized in conjunction with EEG system[35], neuromodulation[17,36,37,38] and neurofeedback devices [39,40] and can also be integrated with advanced machine learning [41,42] approaches to diagnose and intelligently manage peripheral pain conditions.

CONCLUSION

In this paper, an Arduino-controlled innovative electrotherapy unit prototype has been proposed. The designed system efficiently stimulates TENS and FES's peripheral nerves and muscles. Smart Electrotherapy Unit (SET) will bring innovation in rehabilitation and physiotherapy, providing an exhaustive solution to pain management and muscular movement. This cutting-edge technology will allow all users to operate the device single-handedly and perform electrotherapy simultaneously.

AUTHORS' CONTRIBUTION:

The following authors have made substantial contributions to the manuscript as under:
Conception or Design: Muhammad Abul Hasan, Muhammad Danish Mujib
Acquisition, Analysis or Interpretation of Data: Muhammad Danish Mujib, Adeena Zafar, Wafa Hassan Khan, Muhammad Ebaad Khan, Hafsa Muhammad Arif
Manuscript Writing & Approval: Muhammad Danish Mujib, Adeena Zafar, Wafa Hassan Khan, Muhammad Ebaad Khan, Hafsa Muhammad Arif

All authors acknowledge their accountability for all facets of the research, ensuring that any concerns regarding the accuracy or integrity of the work are duly investigated and resolved.

ACKNOWLEDGEMENTS: We thanks all the participants in this study

INFORMED CONSENT: Written Informed Consent was taken from each patient.

CONFLICT OF INTEREST: None.

FUNDING STATEMENTS: None.

ETHICS STATEMENTS: The protocol of the present study was registered by the local ethics committee of NED University of Engineering & Technology, Karachi, Pakistan (Protocol Code: ASRB/1592).

REFERENCES

1. Lin T, Gargya A, Singh H, Sivanesan E, Gulati A. Mechanism of peripheral nerve stimulation in chronic pain. *Pain Med*. 2020 Aug;21(Suppl 1):S6–S12. doi: 10.1093/pm/pnaa164.
2. Chen R, Li M, Ding M. Optogenetic stimulation of the "Zusanli" acupoint alleviates inflammatory pain through active Wnt/β-Catenin and MAPK signaling pathway in rats. *Heliyon*. 2024 Oct 30;10(21):e39992
3. Zhou S, Hussain N, Abd-Elsayed A, Boulos R, Hakim M, Gupta M, et al. Peripheral nerve stimulation for treatment of headaches: an evidence-based review. *Biomedicines*. 2021 Oct 31;9(11):1588.
4. Campbell TS, Johnson JA, Zernicke KA. Gate control theory of pain. In: Gellman MD, editor. *Encyclopedia of Behavioral Medicine*. Cham: Springer International Publishing; 2020; 914–6.
5. Shirley J. The gate theory of pain revisited: modeling different pain conditions with a parsimonious neurocomputational model [Internet]. Accessed: Sep 11, 2024.
6. Rewiring the lesioned brain: electrical stimulation for post-stroke motor restoration [Internet]. Accessed: Sep 11, 2024.
7. Debeuf R, De Vlieger D, Defour A, Feyen K, Guida S, Cuypers L, et al. Electrotherapy in stroke rehabilitation can improve lower limb muscle characteristics: a systematic review and meta-analysis. *Disabil Rehabil*. 2024 Apr 1:1–17.
8. Fernández-Pérez JJ, Serrano-Muñoz D, Gómez-Soriano J, Álvarez DM, Avendaño-Coy J. Selective nociceptive modulation using a novel prototype of transcutaneous kilohertz high-frequency alternating current stimulation: a crossover double-blind randomized sham-controlled trial. *J Neuroeng Rehabil*. 2024 Nov 15;21(1):203.
9. Perez Navarro M, Esquenazi B. Use of transcutaneous electrical nerve stimulation (TENS) for pain management during intrauterine device insertion: a case series. *Cureus*. 2024 Sep 13;16(9):e69324.
10. Alam M, Tabrizi R, Mohammadikhah M, Farzan A, Moslemi H, Farzan A, et al. Effect of transcutaneous electrical nerve stimulation on maximum mouth opening after orthognathic surgery: a randomised controlled trial. *Ann Med Surg (Lond)*. 2024 Sep 30;86(11):6555–60.
11. Inamdar M, Mehendale N. A review on transcutaneous electrical nerve stimulation and its applications. *SN Compr Clin Med*. 2021 Dec;3. doi: 10.1007/s42399-021-01065-1.
12. Chin M, Popovic M. Functional electrical stimulation therapy for restoration of motor function after spinal cord injury and stroke: a review. *BioMed Eng OnLine*. 2020;19. doi: 10.1186/s12938-020-00773-4.
13. Wilson R, Gunzler D, Bennett M, Chae J. Peripheral nerve stimulation compared to usual care for pain relief of hemiplegic shoulder pain: a randomized controlled trial. *Am J Phys Med Rehabil*. 2014 Jan;93:17–28. doi: 10.1097/PHM.0000000000000011
14. Park SJ, Wang JS. The immediate effect of FES and TENS on gait parameters in patients after stroke. *J Phys Ther Sci*. 2017 Dec;29:2212–4. doi: 10.1589/jpts.29.2212.
15. An easy-to-build transcutaneous electrical stimulator for spinal cord stimulation therapy [Internet]. Accessed: Sep 11, 2024.

16. Sonwane A, Patil CY, Deshmukh G. Design and development of portable transcutaneous electrical nerve stimulation device and basic principles for the use of TENS. 2018 May. p. 285–7. doi: 10.1109/ICOEI.2018.8553898.
17. Mujib M, et al. Comparative neurological and behavioral assessment of central and peripheral stimulation technologies for induced pain and cognitive tasks. *Biomedicines*. 2024 Jun;12:1269.
18. Fanninger S, Plener PL, Fischer MJM, Kothgassner OD, Goreis A. Water temperature during the cold pressor test: a scoping review. *Physiol Behav*. 2023 Nov;271:114354. doi: 10.1016/j.physbeh.2023.114354.
19. Mitchell LA, MacDonald RAR, Brodie EE. Temperature and the cold pressor test. *J Pain*. 2004 May;5(4):233–7. doi: 10.1016/j.jpain.2004.03.004.
20. Khan A, Li K, Wei N. Integrated design of functional electrical stimulator and transcutaneous electrical nerve stimulator on a single prototype. 2021 Jul. p. 453–8. doi: 10.1109/ICARM52023.2021.9536149.
21. Sulaiman N, Ibrahim A, Mohd Zaman MH. A programmable transcutaneous electrical nerve stimulation device based on Arduino and remote control using a smartphone. *Int J Adv Technol Eng Explor*. 2021 Feb;8:320–7.
22. Sarkar S. Design of transcutaneous electrical nerve stimulating machine using 555 timer. 2016. doi: 10.21275/ART20162812.
23. Patton E, Tissenbaum M, Harunani F. MIT App Inventor: objectives, design, and development. 2019. p. 31–49. doi: 10.1007/978-981-13-6528-7_3.
24. Pereira S, Mehta S, McIntyre A, Lobo L, Teasell R. Functional electrical stimulation for improving gait in persons with chronic stroke. *Top Stroke Rehabil*. 2012 Nov;19:491–8. doi: 10.1310/tsr1906-491.
25. Howlett OA, Lannin NA, Ada L, McKinstry C. Functional electrical stimulation improves activity after stroke: a systematic review with meta-analysis. *Arch Phys Med Rehabil*. 2015 May;96(5):934–43. doi: 10.1016/j.apmr.2015.01.013.
26. Tashani O, Johnson M. Transcutaneous electrical nerve stimulation (TENS): a possible aid for pain relief in developing countries? *Libyan J Med*. 2009 Jun;4:62–5. doi: 10.4176/090119.
27. In TS, Jung JH, Jung KS, Cho HY. Effectiveness of transcutaneous electrical nerve stimulation with taping for stroke rehabilitation. *Biomed Res Int*. 2021;2021:9912094. doi: 10.1155/2021/9912094.
28. Visconti MJ, Haidari W, Feldman SR. Transcutaneous electrical nerve stimulation (TENS): a review of applications in dermatology. *J Dermatol Treat*. 2020 Dec;31(8):846–9. doi: 10.1080/09546634.2019.1657227.
29. Kaplan B, Rabinerson D, Lurie S, Bar J, Krieser UR, Neri A. Transcutaneous electrical nerve stimulation (TENS) for adjuvant pain relief during labor and delivery. *Int J Gynaecol Obstet*. 1998 Mar;60(3):251–5. doi: 10.1016/s0020-7292(97)00275-0.
30. K. Shahid, "(PDF) A Comprehensive Review of Physical Therapy Interventions for Stroke Rehabilitation: Impairment-Based Approaches and Functional Goals." Accessed: Sep. 11, 2024.
31. S. S. M. Ng and C. W. Y. Hui-Chan, "Transcutaneous electrical nerve stimulation combined with task-related training improves lower limb functions in subjects with chronic stroke," Stroke, vol. 38, no. 11, pp. 2953–2959, Nov. 2007, doi: 10.1161/STROKEAHA.107.490318.
32. E. J. Moore D., "Effectiveness of upper limb functional electrical stimulation after stroke for the improvement of activities of daily living and motor function: a systematic review and meta-analysis - PubMed." Accessed: Sep. 11, 2024.
33. "McNiece Tens Inc.," McNiece Tens. Accessed: Sep. 11, 2024.

34. "Functional Electrical Stimulation Market Size & share to 2033," Functional Electrical Stimulation Market. Accessed: Sep. 11, 2024.
35. L. Farooq et al., "Affordable Design and Implementation of a 4-Channel EEG Bio-signal Amplification System with Mobile App Visualization Interface: Affordable 4-Channel EEG Bio-signal Amplifier," Allied Med. Res. J., vol. 2, no. 2, pp. 226–236, 2024. doi: 10.59564/amrj/02.02/031
36. M. D. Mujib, M. A. Hasan, S. A. Qazi, and A. Vuckovic, "Understanding the neurological mechanism involved in enhanced memory recall task following binaural beat: a pilot study," Exp. Brain Res., vol. 239, pp. 2741–2754, 2021. doi: 10.1007/s00221-021-06132-6
37. M. D. Mujib, A. Z. Rao, M. A. Hasan, A. Ikhlaq, S. A. Buzdar, and S. A. Qazi, "Frontal cortex cooling and modulation of brain frequencies using a wearable Peltier device," Phys. B Condens. Matter, vol. 652, p. 414641, 2023. doi: 10.1016/j.physb.2023.414641
38. M. A. Hasan, H. Shahid, S. A. Qazi, O. Ejaz, M. D. Mujib, and A. Vuckovic, "Underpinning the neurological source of executive function following cross hemispheric tDCS stimulation," Int. J. Psychophysiol., vol. 185, pp. 1–10, 2023. doi: 10.1016/j.ijpsycho.2023.01.004
39. M. A. Hasan, P. Sattar, S. A. Qazi, M. Fraser, and A. Vuckovic, "Brain networks with modified connectivity in patients with neuropathic pain and spinal cord injury," Clin. EEG Neurosci., p. 15500594211051485, 2021.
40. M. Ather et al., "Efficacy of audiovisual neurofeedback training for attention enhancement: a multimodal approach," NeuroReport, pp. 10–1097, 2024. doi: 10.1097/WNR.0000000000002063
41. A. Z. Rao, S. S. Siddique, M. D. Mujib, M. A. Hasan, A. O. Alokaily, and T. Tahira, "Sensor Fusion and Machine Learning for Seated Movement Detection with Trunk Orthosis," IEEE Access, vol. 12, pp. 41676–41687, 2024. doi: 10.1109/ACCESS.2024.3377111
42. S. Marappan, M. D. Mujib, A. A. Siddiqui, A. Aziz, S. Khan, and M. Singh, "Lightweight Deep Learning Classification Model for Identifying Low-Resolution CT Images of Lung Cancer," Comput. Intell. Neurosci., vol. 2022, pp. 1–10, Aug. 2022. doi: 10.1155/2022/3836539.