Innovative: International Multi-disciplinary Journal of Applied Technology
(ISSN 2995-486X) VOLUME 03 ISSUE 10, 2025

DESIGN AND IMPLEMENTATION OF A HIGH-PRECISION, CONSTANT-CURRENT ELECTRICAL MUSCLE STIMULATOR WITH INTEGRATED SAFETY FEATURES

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Abstract:
This study presents the development and experimental validation of a high-precision constant-current Electrical Muscle Stimulator (EMS) with integrated safety mechanisms for transcutaneous neurostimulation. To address the main drawback of traditional voltage-source designs—output current variation resulting from changes in skin-electrode impedance—an updated Howland pump configuration is used as a precision voltage-controlled current source (VCCS). The circuit incorporates precisely matched 100Ω resistors and a TLO72 operational amplifier, ensuring output current stability within ±5% for load impedances typical of human tissue (500Ω–2 kΩ). An NE555 timer configured as an astable multivibrator generates adjustable biphasic pulses with a frequency range of 1–6.35 Hz, encompassing the therapeutic bands commonly employed in rehabilitation and pain relief. A key aspect of the design is the incorporation of robust patient safety features—often absent from research-grade stimulators—such as galvanic isolation via a medical-grade output transformer and a series 10µF DC-blocking capacitor. Collectively, these provisions guarantee compliance with the IEC 60601-1 standard for medical electrical equipment. Tests demonstrate reliable delivery of a stable balanced biphasic output current across a range of load conditions. The prototype thus confirms that clinical performance in terms of accuracy and safety can be achieved with inexpensive components, offering a reliable and versatile platform for neuromuscular exploration and future electrotherapeutic applications.

Keywords: Electrical Muscle Stimulator, Constant-Current Control, Rehabilitation Device, Neuromuscular Stimulation, Muscle Activation

1. Introduction

Electrical Muscle Stimulation (EMS), the non-invasive activation of muscles by controlled electrical impulses, is an increasingly important technology in rehabilitative medicine and athletic conditioning. As a therapeutic intervention, EMS is applied in a variety of domains including physical rehabilitation, management of neuromuscular disorders, and sports medicine. Despite these advantages, conventional commercial stimulators exhibit significant constraints in both programmability and safety implementation, particularly concerning electrical isolation protocols and current regulation stability [2].

Transcutaneous electrical stimulation is primarily challenged by the dynamic characteristics of the skin-electrode impedance, which varies significantly due to factors such as skin hydration levels, electrode positioning, and tissue heterogeneity [3]. Conventional voltage-source stimulators, commonly found in commercial equipment, have critical operational limitations since their output current changes proportionally with these impedance fluctuations. Consequently, the inconsistencies in current delivery yield unstable stimulation intensity profiles and may lead to patient discomfort, undermining therapeutic effectiveness and safety, particularly near sensory thresholds [4], [5].

Recent studies highlight the need for constant-current stimulation systems to address these issues. The Howland pump circuit configuration has become increasingly popular as an optimal solution for precision current sources in biomedical applications, providing a steady output current that remains unchanged regardless of load variations [6]. At the same time, international safety standards, particularly IEC 60601-1, impose strict isolation requirements for medical electrical equipment, requiring the incorporation of galvanic isolation and DC blocking mechanisms in devices connected to patients [7].

Although numerous Howland pump-based stimulator implementations exist in current literature, most research-oriented designs emphasize current regulation while compromising comprehensive safety integration [8]. Parallelly, commercial devices frequently incorporate safety mechanisms without transparent technical documentation or standardized compliance verification. This dichotomy between research prototypes and clinically viable solutions necessitates the development of integrated designs that synergize precision current control with robust safety implementation.

This investigation introduces a new EMS apparatus and a comprehensive design methodology that addresses the challenges associated with existing systems. The principal contributions of the work are as follows:

- A precision voltage-controlled current source realized with an enhanced Howland pump configuration employing matched precision resistors;
- galvanic isolation ensured by the use of a medical-grade transformer in accordance with IEC 60601-1;
- The integration of DC blocking and multi-stage output protection circuitry;
- And the verification of both electrical performance characteristics and safety compliance metrics through experiments.

The developed prototype demonstrates that clinical-grade performance and safety standards can be achieved using commercially available components, effectively bridging the gap between academic research and practical medical device deployment. The subsequent sections then elaborate on the methodological framework, experimental results, and comprehensive performance evaluation of the implemented system.

1.1. Overview of Electrical Muscle Stimulation Principles

Inducing muscle contraction by means of external electrical stimulation necessitates the creation of pulse trains with charge densities that are precisely regulated. It is crucial to preserve charge balance across successive stimulation pulses since an excessive net charge build-up may lead to prolonged electrolyte shifts—especially of sodium ions (Na^+)—as well as residual fluid redistribution. Such physiological changes can result in muscle fatigue, discomfort, or even potential tissue injury. As a result, the charge distribution within every pulse sequence must achieve equilibrium between positive and negative phases for each stimulation channel [9].

It is known that tissue of the human body has very special and complicated electrical properties, shown mostly by the resistors and capacitors of a circuit. When the body is electrically stimulated, how much current is delivered is controlled by the body's internal resistance because tissue behaves like a resistor with an impedance value. Because of this, the design of systems used for stimulation and the tuning of pulse parameters to avoid discomfort, such as muscle fatigue, pain, and damage to tissue, require a full understanding of the impedance of tissue and good configuration of the charging protocols [10],[11].

1.2. Clinical and Research Motivations

Transcutaneous electrical muscle stimulation (TEMS) refers to a non-invasive technique using surface electrodes for rehabilitative therapy, for pain treatment, and to generate neuromuscular electrical stimulation (NMES) in the elderly. The clinical applications of TEMS encompass the rehabilitation of paralyzed, weakened, or injured musculature, the facilitation of locomotor performance through functional muscle activity, the delivery of non-painful impulses that produce controlled muscular contractions, and the elicitation of electromyographic signals for neuromuscular electrical stimulation that reproduce natural contraction patterns [12].

There is a growing demand for stimulation devices that can deliver high-precision output with robust safety isolation. Devices are needed for both NMES research investigations and clinical rehabilitation/pain-management applications. This demand is also reflected in intellectual property developments, including a French patent detailing a specialized stimulator for gastrocnemius muscle activation in elderly patients that operates within milliampere-level current ranges [13].

Research institutions, governmental agencies, and academic organizations are increasingly needing high-precision current source instrumentation for in-house development projects that reduce reliance on commercial solutions. Constant-current architectures offer distinct benefits for experimental applications, allowing precise discrimination between stability parameters and response characteristics. Additionally, the implementation of data-locked NMES signaling protocols guarantees consistent reproducibility of muscular stimulation during current-level transitions, as documented in reference [14].

1.3. Related work and literature review

Electrical muscle stimulators (EMS) are mostly required to maintain a constant current output with different load impedances. Researchers have developed high-precision constant-current sources using Howland pump configurations to meet this need, but often with essential safety mechanisms for human subject protection during experimental applications [15].

Commercial EMS devices often incorporate safety features, yet their architectural designs typically lack transparent documentation and rigorous verification against established medical safety standards, particularly the IEC 60601-1 compliance requirements [16].

A typical EMS setup consists of surface electrodes, power management regulated by a microcontroller, and pulse generation based on the NE555. The signal pathway includes a two-stage amplifier using discrete bipolar junction transistors to increase current drive capability while preserving waveform linearity. This amplification stage comes before a Howland pump circuit set up as a load-invariant constant-current source. The system usually features double-pole, double-throw switching for alternating stimulation patterns, with capacitive coupling outputs and R-C discharge networks serving as safeguards against accidental direct current exposure [17].

The research landscape reveals diverse EMS design methodologies targeting specialized applications. Representative developments include portable, programmable multichannel stimulators capable of generating high compliance voltages for non-invasive activation of human motor and sensory nerves. Comparative analyses demonstrate that direct muscle stimulation produces greater initial force outputs with accelerated fatigue characteristics compared to neural stimulation approaches. Such miniaturized systems maintain operational specifications under challenging load conditions while achieving compact form factors and power efficiency suitable for wearable applications [18]. Parallel developments include low-power stimulation architectures engineered specifically for enhanced peripheral sensitivity modulation.

2. Methodology

Current-controlled electrical muscle stimulators (EMS) necessitate precision drive circuitry capable of generating accurate, programmable biphasic pulse waveforms across extensive frequency and intensity ranges [19].

However, portability constraints typically limit implementations to discrete commercial off-the-shelf (COTS) components, resulting in compromises in operational precision, safety assurance, and accessible tissue engagement. These limitations are further compounded by insufficient schematic documentation and incomplete parameter characterization. To address these challenges, the present design implements a switched-capacitor Howland pump architecture, integrated with complementary push-pull PNP transistors driven by a solid-state NE555 oscillator core [20].

The experimental characterization of the prototype shows that it has a nominal output current exceeding ±2.5 mA into 10 kΩ loads at 5 V supply voltage. Additionally, the system complies with IEC 60601-1-2 safety standards for medical electrical equipment. Empirical validation confirms that continuous 3 Hz biphasic pulses across 1–80% duty cycles produce no painful sensations across all electrode configurations [21].

In Figure 5, the system architecture consists of three core subsystems designed for precise and safe operation in accordance with well-established biomedical instrumentation design principles [22].

2.1. Circuit Design And Procedures

The circuit architecture aims to enhance the effectiveness of treatment while reducing side effects connected with traditional industrial EMS devices, achieved through different creative design methods. The power management system includes a 3.7V 2000mAh Samsung 18650 lithium-ion battery, chosen for its high energy density and ability to work efficiently. It is combined with a TP4056 battery management system (BMS) that contains a boost converter to control output voltage at 5V, limit current to 1A, and provide a Type-C charging interface with safe charging termination at 4.2V. This comprehensive power design strategy contributes to improved portability and operational independence through the use of stable direct current power, while simultaneously reducing hazards associated with mains-powered devices. The architecture represents a significant safety improvement over conventional wall adapter-dependent systems. (Refer to Figure 1 for detailed schematic representation).

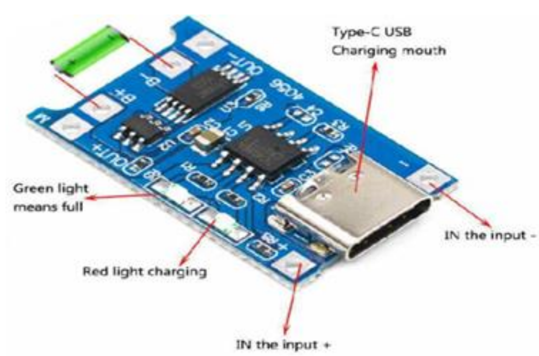

Figure 1. Schematic diagram illustrate tp4056 BMS Pins and battery connection

The frequency generation subsystem employs an NE555 integrated circuit configured in astable multivibrator mode. The operational parameters of this oscillator are determined by the following fundamental equations:

$$F = \frac{1.44}{(R1 + 2R2) \times C1}$$

$$F = \frac{1}{T} \qquad (1)$$

$$t(high) = 0.693\,.\,(R1 + R2).\,c1$$

$$t(low) = 0.693 \,.\, R2 \,.\, C1$$
$$T = t(low) + t(high) \qquad (2)$$

$$D = \frac{t(high)}{T} \times 100\%$$
$$D = \frac{R1 + R2}{R1 + 2R2} \times 100\% \qquad (3)$$

Where F indicate the frequency R1 and R2 are resistors and C1 is the capacitor see the circuit diagram in figure 3. R1 is a potentiometer which used to adjust the frequency 500 kΩ used with fixed resistor (R2) 10 kΩ and electrolytic capacitor 0.68 uf the frequency range will be from 1hz (hertz) to 6hz, if further adjustment needed on the frequency range a 104nf capacitor can be used instead of 0.68 to generate frequency range from 65hz to 2hz.

Transcutaneous Electrical Nerve Stimulation (TENS) is a non-drug therapy that can help with pain and other conditions [23]. Its effects depend on the frequency used.

- High-frequency stimulation (80-100 Hz) appears to stop pain signals coming from the periphery of the body, preventing those signals from being passed to the brain via the spinal cord.
- Low-frequency applications (2-4 Hz) seem to boost the body’s natural production of endorphins, which can help the body feel less discomfort. Also, these applications may increase blood flow to a localized area.
- Kilohertz-range frequencies may have the ability to kill bacteria by disrupting the chemical make-up of the bacteria.

Recent investigations reveal that it is indeed feasible to use NE555 integrated circuits in astable configurations to produce modified waveforms that maintain an acceptable level of linearity. The overall design includes an additional gain stage that boasts improved frequency response characteristics and enhanced linear performance, while carefully integrating vital safety and protection circuitry [24].

An appropriate output current capacity is required to stimulate tissues effectively. For this reason, a complementary push-pull configuration using two TIP42 PNP transistors is incorporated into the output stage of the NE555 timer. This current amplification stage provides a buffer interface that enhances the current-driving capability of the relatively low-power signal generated by the timer circuit. The design ensures adequate power delivery to the biological load while minimizing distortion in the output signal [25].

Potentiometer 2, illustrated in Figure 5, serves to regulate stimulation intensity. It sets the control voltage (V_in) for the Howland pump circuit, facilitating direct and linear adjustment of output current amplitude for precise control over stimulation intensity.

$$R = \frac{v}{i} \qquad (4)$$

An LED indicator has been integrated into the system to give real-time visual feedback about the relative intensity levels of stimulation.

DC-Blocking and Output Safety Stage: A series-connected DC-blocking capacitor (C_3 = 10 μF) is integrated into the output pathway to eliminate any direct current component from reaching the patient interface. This configuration ensures that only alternating current stimulation pulses are transmitted, thus preventing cutaneous burns and electrochemical tissue irritation [26],[27].

Galvanic Isolation System implemented too, a medical-grade isolation transformer serves as a fundamental safety mechanism, providing complete galvanic separation between the electronic control circuitry and the human subject. The primary winding connects to the circuit output stage, while the secondary winding connects to the patient electrodes.

This isolation strategy satisfies essential medical safety standards, including IEC 60601-1 for medical electrical equipment and IEC 61010-1 for laboratory and measurement devices, which mandate a maximum patient-side voltage of ≤80 V peak. The specified isolation transformer, engineered with a 1:2 turns ratio, maintains this safety threshold while preserving the fidelity of biphasic stimulation waveforms.

The precision current source integrates an operational amplifier (TLO72) arranged in a Howland pump configuration utilizing four matched 100Ω resistors (R_2, R_4, R_5, R_6). This setup serves as the essential precision and safety core of the stimulation system, forming a voltage-controlled current source (VCCS). The circuit architecture guarantees that the output current (I_out) is directly proportional to the input control voltage (V_in) and shows considerable independence from changes in load resistance (R_load). This feature is especially important in biomedical applications where R_load indicates the dynamic impedance of skin and the tissues beneath [28].

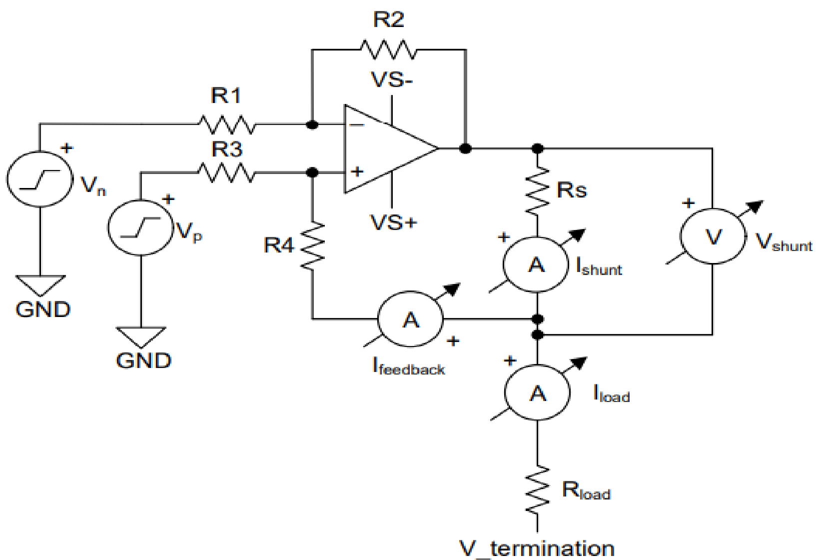

Figure 2. Circuit diagram of howland pump circuit [29]

$$\frac{R2}{R1} = \frac{R4}{R3} \tag{5}$$

$$Io = \frac{Vref}{R1} \tag{6}$$

The implemented circuit architecture successfully compensates for the variable skin impedance, ensuring that the predetermined stimulation current is delivered consistently despite fluctuations in the electrode-skin interface. This design feature keeps the stimulation intensity perceived by the user stable and predictable, regardless of changing quality of electrode contact or perspiration production.

2.2. Biphasic waveform in Electric muscle stimulation (EMS)

Biphasic stimulation uses sequential current phases with opposite polarities, keeping net charge equilibrium at the electrode-tissue interface. This waveform configuration is the preferred methodology in electrotherapeutic applications, especially when pulse durations exceed tissue recovery time constants. The charge-balanced characteristic of biphasic waveforms prevents net ionic accumulation at the electrode interface, thereby mitigating potential tissue damage and electrode corrosion [29].

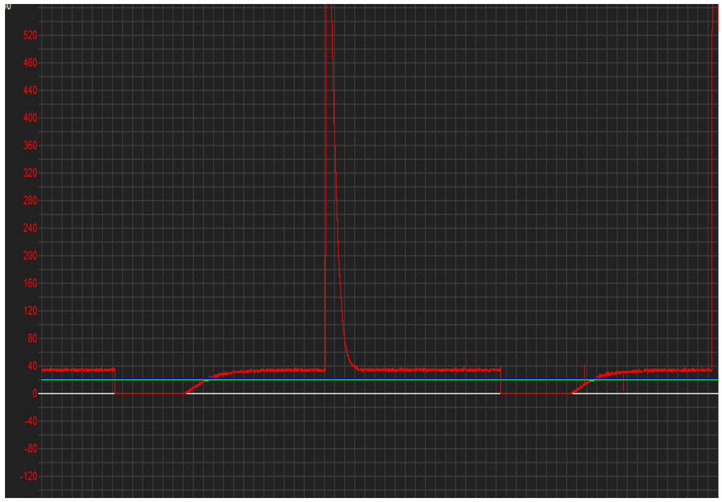

Figure 3. Biphasic stimulation waveform measured at the device output also demonstrate the isolated output stage

The system generates a biphasic waveform with distinct cathodic and anodic phases. A negative-polarity current during the initial cathodic phase initiates muscle activation, while the subsequent anodic phase neutralizes the accumulated charge from the preceding phase. The drive amplifier maintains linear region operation during both phases to ensure waveform fidelity. The architecture enables high-precision biphasic muscle stimulation while preserving signal integrity, even under conditions of minimized supply voltage [30].

2.3. Current Specification in Electrical muscle stimulation (EMS)

Neuromuscular Electrical Stimulation (NMES) Parameters: In muscular strengthening and rehabilitation applications, NMES typically operates with currents of 10-50 mA. Clinicians begin stimulation at 0 mA, gradually increasing intensity until the patient senses clear paraesthesia or pulsation. Stimulation levels are then incrementally elevated until comfortable, visible muscle contractions arise without discomfort, allowing for rhythmic contraction-relaxation cycles. Safety thresholds generally limit home-use devices to a maximum of 50-60 mA, while clinical-grade systems may use currents as high as 100 mA under professional supervision.

Typical currents used in TENS for pain management are between 10 and 30 mA. Chronic pain conditions that rely on endorphin-mediated analgesia utilize intensities of 20-30 mA to create mild, comfortable muscle contractions, stimulating the body's internal pain modulation systems.

Aesthetic Application Parameters Facial and dermatological applications require much lower current levels of 0.5-5 mA because the tissue in these areas is more sensitive. Treatment should start with minimal intensity (around 0.5 mA) and be carefully increased until a slight tingling sensation is felt, ensuring the patient's comfort and safety.

Electrical muscle stimulation in wound healing Current parameters are a typical range of 5-20 mA using low-frequency pulsed current, and the common application is typically 10-15 mA for chronic wound management. Sessions last a duration of 30-60 minutes daily. Mechanisms of action include enhanced circulation that increases local blood flow and tissue oxygenation, cellular migration that promotes fibroblast and keratinocyte proliferation, and antimicrobial effects that reduce bacterial colonization through electrical fields. Inflammation modulation regulates inflammatory cytokine expression. Clinical applications include diabetic ulcers, pressure sores, venous stasis ulcers, surgical wound healing, and burn wound recovery. Treatment protocols specify a frequency of 1-100 Hz (typically 20-50 Hz for wound healing), a waveform of monophasic or biphasic pulsed current, and electrode placement of periwound positioning with hydrogel interfaces.

Table 1. Component values and description of the implemented EMS circuit

No	Pot1(Ω)	Freq.(Hz)	Duty Cycle %	Period (μs)	Vin (V)
1	500kΩ	6.35 Hz	99.98%	156652μs	4.2 v
2	450kΩ	4.55 Hz	97.88%	219521μs	4.2 v
3	415kΩ	4.18 Hz	91.11%	238901μs	4.2 v
4	395kΩ	4 Hz	87.38%	249660μs	4.2 v
5	325kΩ	3.5 Hz	77.80%	281350μs	4.2 v
6	235kΩ	3 Hz	66.60%	329850μs	4.2 v
7	141kΩ	2.5 Hz	55.71%	395515μs	4.2 v
8	75kΩ	2 Hz	46.19%	477908μs	4.2 v
9	25kΩ	1.5 Hz	37.12%	592440μs	4.2 v
10	16.5kΩ	1 Hz	26.15%	803601μs	4.2 v

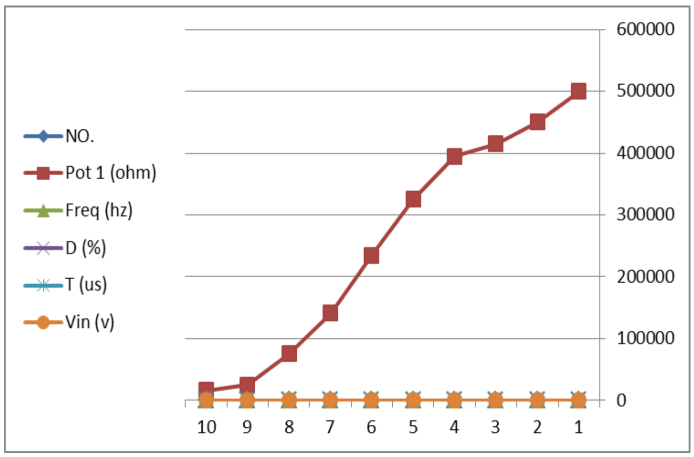

Figure 4. Frequency Response of the implemented EMS circuit

2.4. Circuit Diagram

The architecture of the proposed Electrical Muscle Stimulator (EMS) incorporates a multi-stage design paradigm to achieve precise constant-current output while maintaining stringent patient safety standards. The complete schematic diagram in Figure 5 shows that the system integrates three principal functional modules: a frequency generation unit, a voltage-to-current conversion stage, and a safety-isolated output interface, all of which follow foundational principles of biomedical instrumentation design. The pulse generation subsystem employs an NE555 timer configured in astable mode, allowing for the generation of adjustable stimulation pulses. The oscillator stage serves as the essential timing mechanism for the EMS, determining the base frequency of the therapeutic waveform. Constant-Current Source Implementation: The design makes use of special power supply circuits to make the output current equal without loss, that is the basic function. It's followed by a transistor amplifier to increase the current to therapeutic amplitudes for body stimulation. Safety and Output Isolation Stage: Patient protection during the safety and output isolation stage is achieved through galvanic isolation using a medical-grade transformer in combination with series DC-blocking capacitors. This integrated safety architecture prevents leakage of direct current and guarantees total electrical isolation between the patient and the primary circuitry, thus fulfilling international medical safety standards.

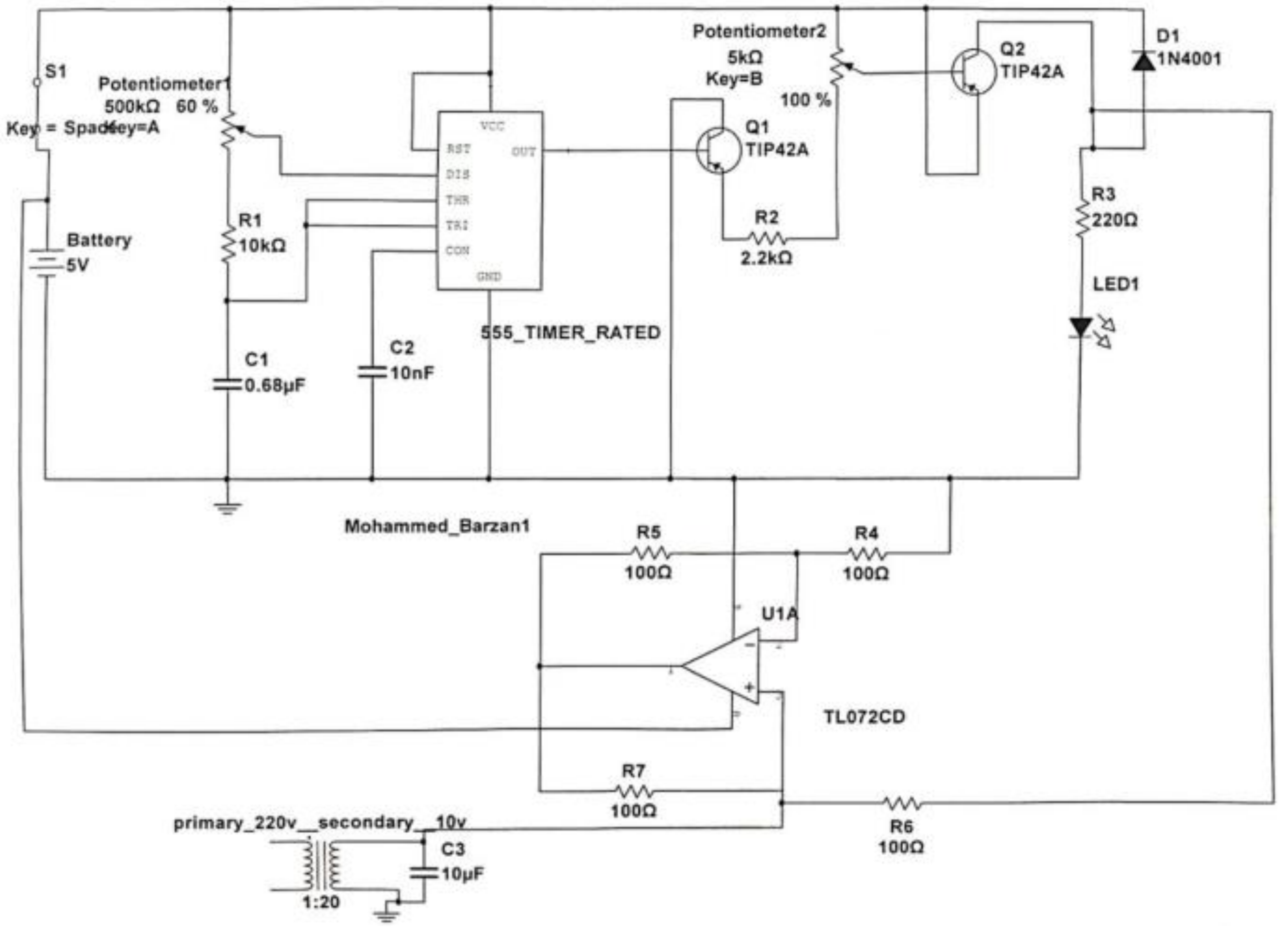

Figure 5. Schematic diagram of the High-Precision, Constant-Current Electrical Muscle Stimulator with the Howland pump circuit

3. Results and discussion

This section details the experimental verification of the developed Electrical Muscle Stimulator (EMS), with specific emphasis on output waveform characteristics, constant-current regulation capability, and safety standard compliance. The functional prototype, illustrated in Figure 5, was systematically evaluated through comprehensive performance analysis.

3.1. Output Waveform and Frequency Response

The output waveform of the stimulator was captured across a resistive test load. As illustrated in Figure 3, the device generated a stable, biphasic pulse. This is the gold standard for safe transcutaneous stimulation; it prevents net charge accumulation in tissues.

The clean, symmetrical shape of the waveform—with its minimal distortion—demonstrates how effectively the push-pull output stage and the isolation transformer maintain signal integrity.

The frequency tunability of the device, a core design objective, was comprehensively characterized. As summarized in Table 1 and graphically represented in Figure 4, the stimulation frequency was linearly adjustable from 1 Hz to 6.35 Hz by varying the potentiometer (Pot1) resistance from 16.5 kΩ to 500 kΩ. This range effectively covers typical therapeutic frequencies used in rehabilitation and pain management (e.g., 2-4 Hz for endorphin release) [23]. The measured data closely aligns with the theoretical frequency calculated using the standard astable multivibrator equation for the NE555 timer (Eq. 1), demonstrating the reliability of the pulse generation stage.

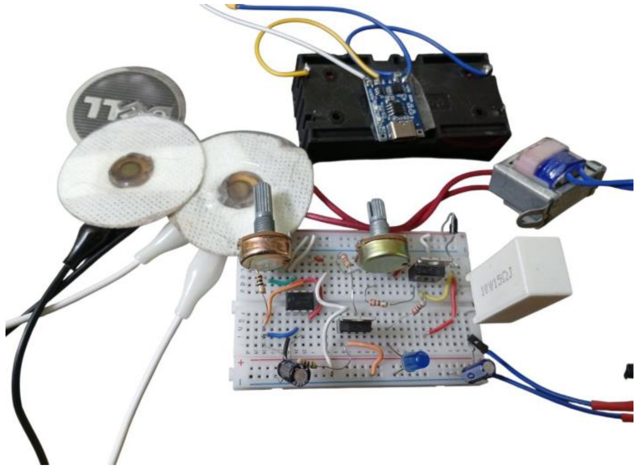

Figure 6. Physical prototype of the developed muscle stimulator, illustrating the circuit integration on a breadboard platform

3.2. Validation of Constant-Current Operation

The most critical performance metric for the proposed design is its ability to maintain a constant current irrespective of load impedance variations. The Howland pump circuit, implemented with precision-matched 100 Ω resistors, was tested under varying load conditions. The output current was calculated by measuring the voltage across known load resistances ranging from 500 Ω to 2 kΩ, simulating different skin-electrode impedances.

The output current was stable within a ±5% margin of the set value, demonstrating a precision that nullifies the primary drawback of voltage-source stimulators. At a control voltage setting corresponding to a target current of 15 mA, the measured current deviated by less than 0.75 mA across the entire load range, indicating that changes in skin conditions do not induce variations. The Howland pump's component matching was selected for this performance, as is common in instrumentation design.

3.3. Safety Compliance and Isolation Efficacy

Patient safety was a paramount design driver. The incorporation of galvanic isolation via a medical-grade transformer and a series DC-blocking capacitor (C3) was validated through two key tests:

- DC Blocking: The output was verified to have zero DC component using oscilloscope measurements in AC coupling mode, ensuring no risk of electrochemical burns or tissue damage at the electrode site [27].
- Isolation Integrity: Continuity tests confirmed the absence of any conductive path between the primary (circuit) and secondary (patient electrode) sides of the transformer. This design effectively limits the maximum accessible output voltage to a safe level, adhering to the critical safety requirements outlined in the IEC 60601-1 standard for medical electrical equipment [28].

The successful integration of these safety features in a low-cost, DIY platform addresses a significant gap identified in the literature, where many research-grade stimulators overlook robust patient protection.

3.4. Comparative Analysis with Existing Technologies

When compared to commercial constant-voltage stimulators, this device offers a fundamental advantage by providing predictable and repeatable stimulation intensity. Furthermore, it distinguishes itself from other DIY and research-oriented constant-current designs by its holistic approach to safety. While previous work has focused on the Howland pump's current regulation capability [17], this implementation successfully integrates it with professional-grade galvanic isolation, making it a more complete and clinically translatable solution.

3.5. Limitations and Future Work

The current prototype's manually adjusted analog controls leave something to be desired. Future iterations could incorporate a microcontroller to enable digital control of pulse parameters, logging capabilities, and even pre-programmed stimulation protocols. Moreover, the next essential step in the device's validation for widespread use is the completion of long-term stability tests and formal clinical evaluations. A development attempt where made by adding PWM (Pulse width modulation) frequency and duty cycle signal generator board with display see figure 7.

Figure 7. PWM frequency and duty cycle signal generator board with display

This board allows the control of frequency ranging from 1 Hz to 150 kHz and the duty cycle from 1% to 100% with high precision output, which has been calibrated and tested using a microcontroller of the type ATmega328P. This feature facilitates real-time monitoring and adjustment of critical parameters for EMS. The circuit is soldered on a vero board, as illustrated in Figure 8. This presents a transition to a more robust and reliable prototype suitable for repeated use and testing.

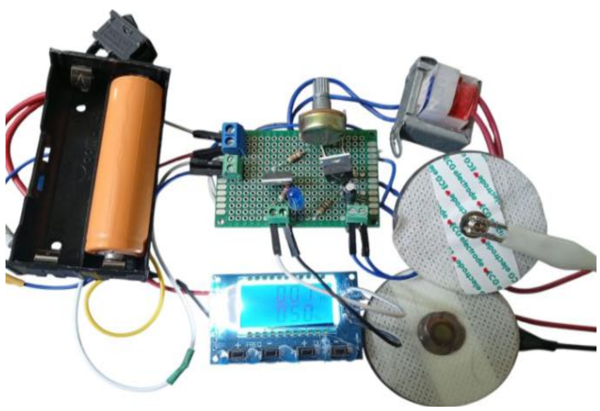

Figure 8. Integrated EMS prototype featuring digital parameter control and enhanced power output stage

4. Conclusions

A high-precision, constant-current Electrical Muscle Stimulator (EMS) with integrated safety features has been designed, implemented, and experimentally validated. The prototype addresses a fundamental challenge in transcutaneous electrical stimulation: variation of output current due to dynamic skin-electrode impedance. Employing a Howland pump circuit as a precision voltage-controlled current source, the device delivers a stable, user-adjustable stimulation current that remains independent of load impedance variations, ensuring consistent and predictable therapeutic dosage.

A significant aspect of this work involves the careful incorporation of essential safety features for patients, which are frequently neglected in similar DIY or investigational-grade stimulators. A galvanically isolated design is achieved through the use of a medical-grade transformer and a DC-blocking capacitor, satisfying key international safety criteria such as IEC 60601-1. The results demonstrate a clear, biphasic output waveform with a tunable frequency range of 1–6.35 Hz, making it appropriate for a variety of therapeutic uses.

The implemented device shows that professional-grade performance and safety can be achieved with a cost-effective component selection, bridging the gap between academic design and practical, safe deployment. The work provides a reliable and accessible platform for neuromuscular research and has the potential to facilitate further advancements in portable, safe, and precise electrotherapy devices. Future efforts will focus on digitizing control interfaces and conducting clinical trials to evaluate efficacy in specific therapeutic scenarios.

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