Development of a Proof-of-Concept Portable Electrostimulation Device for Lower Limbs Blood Flow Enhancement

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Abstract: This paper presents the design and implementation of a proof of concept of a wearable electrostimulation device aimed at improving blood flow in the lower limbs. The portable system, integrated into wearable compression socks, delivers electrical pulses for muscular stimulation in specific areas of the leg, using conductive yarns in their structure, promoting better blood flow. This device addresses the growing sedentary lifestyle and the resulting health issues like poor circulation, which can lead to severe complications. It features Bluetooth Low Energy (BLE) communication for real-time session control via a mobile application. The preliminary results demonstrate effective electrical stimulation, validated through testing, ensuring the feasibility of the system.

1 INTRODUCTION

In modern society, sedentary lifestyles are increasingly prevalent, characterized by prolonged periods spent sitting, often in front of screens or during commutes. This lack of physical activity leads to insufficient stimulation of the lower limb muscles, resulting in impaired blood circulation. Over time, this condition can escalate to serious complications, including chronic venous insufficiency, tissue damage, and, in severe cases, lower limb failure. Prolonged lack of circulation, if unaddressed, may necessitate amputation and could even be fatal (Higgins, et al., 2022). While physical exercise such as walking or running is critical for maintaining healthy blood flow, not everyone can engage in regular activity due to professional, medical, or personal constraints. Consequently, alternative solutions, including pharmacological interventions and devices designed to stimulate leg muscles and enhance blood flow, have gained prominence as viable approaches to mitigating these risks. (Ashutosh , Dhaniwala, Dudhekar, Goyal, & Patel, 2023)

Currently, portable stimulation devices are predominantly designed for the abdominal region, offering limited applicability to other parts of the body. For the lower limbs, existing equipment tends to be large and cumbersome, requiring patients to remain stationary, often lying on a stretcher, to receive treatment. This lack of portability and

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practicality restricts their usability in daily life or during routine activities.

In contrast, compression socks are widely used in sports such as running and walking to improve blood flow through passive pressure applied by the tightness of the textile structure. However, these socks provide only static compression and lack the capability to actively stimulate lower limb muscles, which is essential for enhancing venous return and addressing more severe circulatory deficiencies.

This gap highlights the need for a portable, user-friendly solution that combines the benefits of compression socks with active muscle stimulation. Such a device could be seamlessly integrated into compression socks to provide dynamic, localized stimulation, offering a more effective approach to improving blood flow in the lower limbs. This innovative approach would be particularly beneficial for individuals with sedentary lifestyles, athletes seeking enhanced recovery, and patients undergoing rehabilitation.

In response to this need, a wearable device was developed as a proof of concept to improve blood flow in the lower limbs through targeted and responsible use. This innovative device delivers electrical pulses to stimulate specific muscle groups in the lower legs, enhancing circulation and promoting venous return.

The wearable system is designed to be compact and portable, seamlessly integrating with compression socks that conduct the electrical stimulation to precise anatomical points. By combining the passive benefits of traditional compression with active muscle stimulation, this device addresses the limitations of existing solutions.

A key feature of the device is its integration of Bluetooth Low Energy (BLE) communication, enabling remote control and customization through a dedicated mobile application. This functionality allows users to tailor treatment sessions, including adjusting stimulation intensity and duration, to meet individual therapeutic or preventative needs.

This paper is organized into five sections. Section 2 provides an overview of the concept of electrostimulation, its application as a therapeutic approach for humans, and the associated benefits. Additionally, existing market solutions are reviewed to identify gaps and opportunities for improvement in addressing lower limb blood flow issues. Section 3 introduces the proposed solution, detailing its development across three core components: hardware, firmware, and software. This section outlines the design process, technical specifications, and integration of these elements to create a functional and effective wearable device. Section 4 focuses on validation tests and results. This includes an evaluation of the device's performance, a demonstration of its usability, and a presentation of the final product, which comprises a compression sock enhanced with silver-plated textile yarn and the wearable device with Bluetooth connectivity. Finally, Section 5 summarizes the challenges, limitations, and lessons learned throughout the development process. Potential areas for improvement are discussed, along with suggestions for future iterations to enhance the device's functionality and usability in subsequent versions of the project.

2 STATE OF ART

Electrostimulation devices are widely available today, with each system employing its own unique mechanisms of operation. Muscle electrostimulation involves the application of an electric current—typically low or medium frequency—through electrodes positioned on the skin. This technique can induce muscle contractions, facilitating functional movements or enhancing muscle strength to improve physical performance.

Electrostimulation systems have found extensive application in both physiotherapy and sports. They are commonly used for the prevention, treatment, and management of various disorders affecting the neuromuscular system. When applied appropriately, these systems represent a safe and effective method for promoting neuromuscular function and improving overall physical health (Sausport, 2024).

2.1 Electrostimulation

The use of electrostimulation dates to ancient times when electric eels were employed to alleviate pain in limbs. Over the centuries, advances in understanding the effects of different waveforms on muscle and nerve function have allowed for the safe and effective application of electrostimulation to optimize patient outcomes in alignment with specific care plans. A fundamental understanding of the properties of electricity and current flow is essential for the safe use of electrostimulation on the human body.

Current flow is governed by its direct proportionality to voltage and inverse proportionality to resistance. Biological tissues exhibit varying electrical properties: the skin, like nerve and muscle membranes, possesses capacitance, enabling it to store electrical charges and resist changes in current flow. Meanwhile, skin and fatty tissues act as

resistors, opposing current flow. The current naturally follows the path of least resistance within the body, driven by ionic flow—positive and negative charges attract, while like charges repel (Stillings D., 1975), (Heidland, et al., 2013).

Figure 1 illustrates the working principle of electrostimulation. The anode and cathode serve as points of contact with the skin and carry opposite charges. At the anode, negative ions migrate toward the positive pole, resulting in increased acidity, protein coagulation, and tissue hardening. Conversely, at the cathode, positive ions migrate toward the negative pole, causing increased alkalinity, protein liquefaction, and tissue softening. These processes contribute to improved circulation as the body strives to restore homeostasis and maintain a neutral pH level (College, 2024).

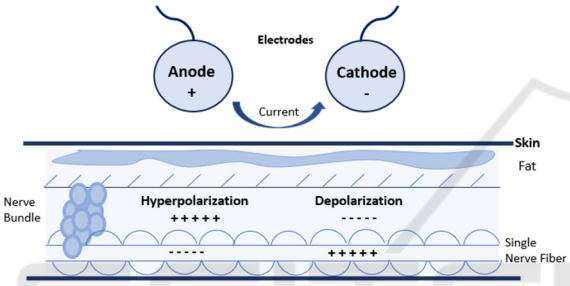

Figure 1: Principle of operation of electrostimulation.

Today, numerous commercial electrostimulation solutions are available, each offering various control modes and therapy session options. However, all these systems are fundamentally based on two core electrostimulation concepts (Digital, 2024):

- Muscle Electrostimulation (EMS) involves the application of low-voltage stimuli, typically with currents ranging from 80 to 100 mA and frequencies between 10 and 100 Hz. EMS primarily targets the motor nerve fibres of muscles to induce muscle contractions. This method is commonly used for muscle strengthening and rehabilitation.
- Transcutaneous Electrical Nerve Stimulation (TENS) is primarily employed for pain management by blocking pain signals. Unlike EMS, TENS uses electrodes placed on sensitive nerve points rather than motor nerve fibres. This stimulates the production of endorphins and provides small electrical impulses that activate pain-modulating mechanisms in the body.

In summary, both EMS and TENS deliver electrical impulses through electrodes placed on the skin near the target area, but they serve distinct purposes: TENS aims to alleviate pain, while EMS is used to relax, strengthen, and improve muscle function. The repetitive muscle contractions induced by EMS promote enhanced blood circulation, prevent muscle atrophy, stimulate muscle growth, aid in muscle relaxation, and reduce inflammation.

Given the objective of this project—to develop a device that enhances blood circulation—a Muscle Electrostimulation (EMS) device was identified as the most suitable choice due to its direct impact on improving blood flow through muscle activation.

2.2 Current Solutions and Standardization

By analysing several commercial models, we identified several common characteristics, including:

- Wireless operation, powered by compact, portable batteries.
- Simple electrodes and pads designed for skin contact.
- Technical specifications, including voltage, current, and frequency parameters.

In the context of available commercial solutions, many devices exhibit similarities to the EM49 model (Beurer, 2023), as shown in Figure 2. This model exemplifies the standard design and functionality commonly seen in the market.

Figure 2: Equipment EM49 (Beurer, 2023).

This equipment is manufactured by Beurer and operates with a maximum voltage of 100Vpp and a current of up to 200mA. Additionally, OMRON produces devices such as the HeatTens (HV-F311-E) (OMRON, 2023), which operates at 70V and can generate 100µs pulses.

A significant portion of the scientific literature focuses on the development of human-machine interfaces, where users can control the activation and deactivation of electrostimulation signals. However, the electrostimulation signals themselves are typically generated and managed by compact commercial devices, such as power supplies, which often lack advanced electrical consumption management (De Almeida, Bertucci Borges, & de

Azevedo Dantas, 2022), (Özgüner, Alaca, Başkurt, & Akman, 2021). Furthermore, some studies fail to consider dynamic and user-centred interactions, as many systems use static signals that cannot be modified. In many cases, these solutions are presented as mere proof-of-concept projects rather than fully developed, functional systems (Velloso, 2005).

3 DEVELOPED WEARABLE DEVICE

The developed solution consists of three main components:

- *Firmware*: This component manages the control of the electrostimulation waveform, as well as the reception, processing, and transmission of messages between the system and the smartphone.
- *Hardware*: This encompasses all the electrical circuits necessary for the system's operation, including power supply, control circuits, and actuation mechanisms.
- Software: A mobile application that enables the creation, editing, and monitoring of electrostimulation sessions.

Figure 3 illustrates the system architecture, highlighting the key modules, including the embedded system responsible for controlling the electrostimulation of the socks through I/O signals. The embedded system also facilitates Bluetooth communication with the mobile application, enabling seamless interaction and control.

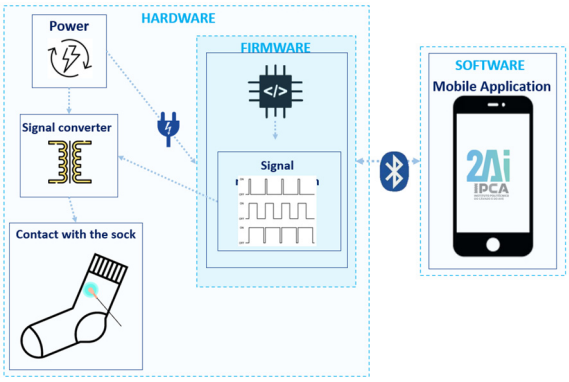

Figure 3: Electrostimulation system architecture.

3.1 Firmware

The ESP32 (Espressif, 2023) was selected as the microcontroller for the system due to its integrated Bluetooth Low Energy (BLE) communication capabilities and dual-core architecture, which allows for the simultaneous execution of two tasks. The roles of the two cores are as follows:

- *Core 0*: Responsible for the initial configuration of interfaces, services, and events. Once configured, it handles the reception of messages and manages notifications related to BLE characteristics.
- *Core 1*: Dedicated to processing and executing the control of the electrostimulation signal, ensuring proper modulation and operation of the stimulation.

Figure 4 illustrates the operational workflow of the electrostimulation module, focusing on the firmware development and task management across the two cores.

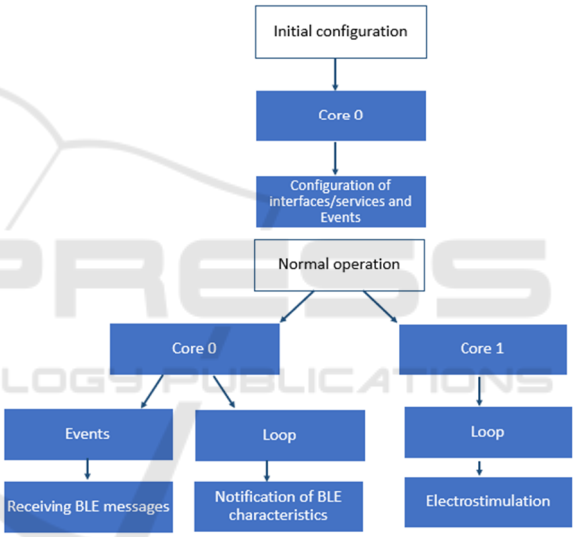

Figure 4: Configuration and operation of the electrostimulation module.

3.2 Hardware

The hardware module developed includes several blocks, including battery management and signal modelling.

3.2.1 Battery Management

One of the requirements of the system was to use an internal lithium battery that could be charged via 5V, the most common nowadays. The MCP73831-2-OT (Farnell, 2023), was used to control battery charging via USB. This is a low-cost and widely used controller. Figure 5 illustrates the battery charging circuit designed for the solution.

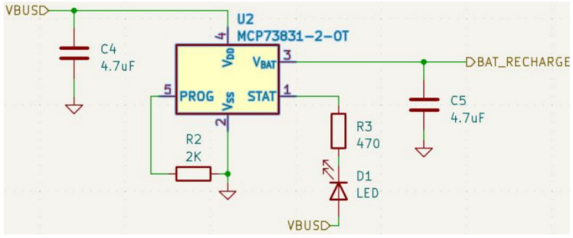

Figure 5: Lithium battery charging circuit.

3.2.2 Electrostimulation Signal Modeling

To model the electrical signal needed to stimulate the muscle, the following steps are required:

- *Raising the electrical voltage*: The module's battery was 3.7V, and it was needed to raise the voltage (45V in this case).
- *Limit current*: Control the maximum current to prevent damage to the user during electrostimulation, such as electrical discharges.
- *Reverse current direction*: To have a two-phase signal, it was needed to change the current direction.

In Figure 6, one can graphically see the various blocks for modeling the electrical signal.

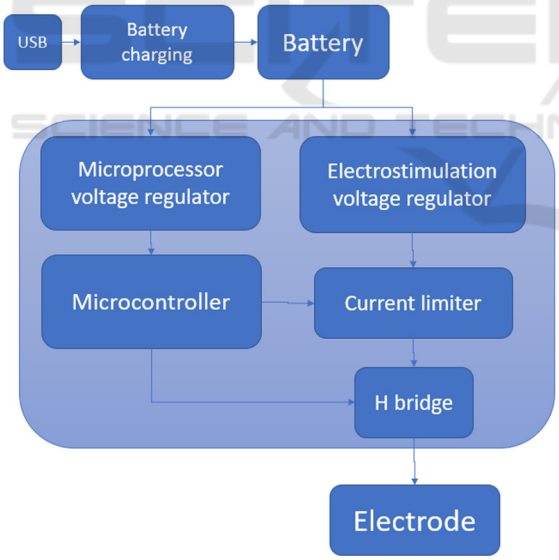

Figure 6: Electrical signal modeling.

Initially, to raise the voltage, were integrated two booster circuits connected in series. An initial one that powers up 3.7V to 5V and a second one that powers up 5V to a maximum of 60V.

The TPS61022RWUR (Instruments, TPS61022 | Buy TI Parts | TI.com, 2024) was used for the first regulator, whose main function was to guarantee a fixed 5V for the next regulator, even if the voltage supplied by the battery decreases. It also has the possibility of ON/OFF control, using the Enable pin.

The circuit developed for the first booster is shown in Figure 7.

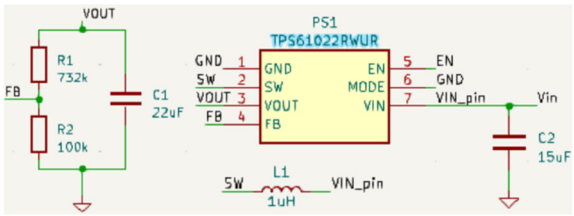

Figure 7: Circuit with the TPS61022RWUR.

Connected in series to the TPS61022RWUR is the TPS55332QPWPRQ1 (Instruments, TPS55332-Q1 | Buy TI Parts | TI.com, 2024). This booster can adjust the output voltage up to 60V. Figure 8 shows the module in the schematic developed.

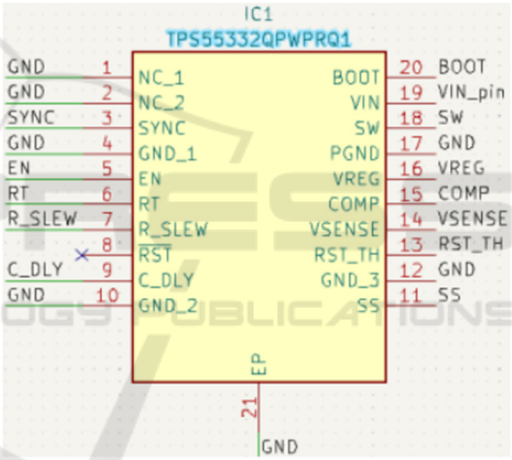

Figure 8: Circuit with TPS55332QPWPRQ1.

The output voltage is set using the ratio of resistors between the VREG and VSense pins, according to the formula on the datasheet (Instruments, TPS55332-Q1 | Buy TI Parts | TI.com, 2024). However, a potentiometer that has a range of values within the desired range has been placed, so fine-tuning is done a posteriori, and with the stability of the system, the value of the precision resistor to be placed to replace the potentiometer will be defined. The voltage configuration circuit used in this project is shown in Figure 9.

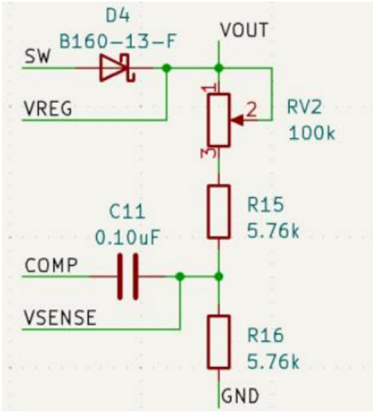

Figure 9: TPS55332QPWPRQ1 output voltage configuration circuit.

In this way, it was possible to obtain a final output voltage of 45V. Having that assured, it was necessary to limit the current. It was used a current mirror circuit, in which two BJT (Bipolar Junction Transistor) transistors and a resistor guarantee a fixed and stable current at the output.

Simulation software was used to help with the development, and it was concluded that a resistance of 2kΩ is needed to guarantee 20mA at 40V.

A potentiometer operating in the desired range of values was placed in the module to be adjusted according to the simulation and guarantee the output current. The transistors selection was according with the desired voltages and currents, resulting in the circuit shown in Figure 10.

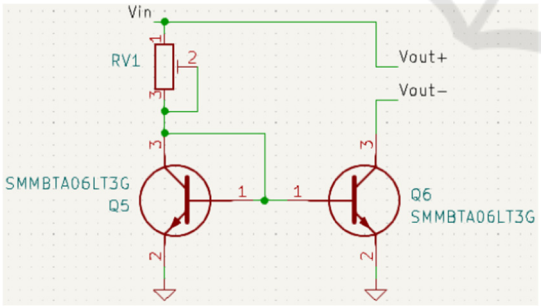

Figure 10: Portable module current mirror circuit.

With the voltage and current stabilized, it was necessary to create a circuit capable of creating a two-phase pulse. To do this, an H-bridge circuit was developed. This circuit used *mosfets* controlled by signals from the microcontroller. These control signals were isolated using optocouplers to avoid damaging the ESP32. All the components were chosen according to the voltages and currents circulating in this part of the circuit. The H-bridge developed is shown in Figure 11.

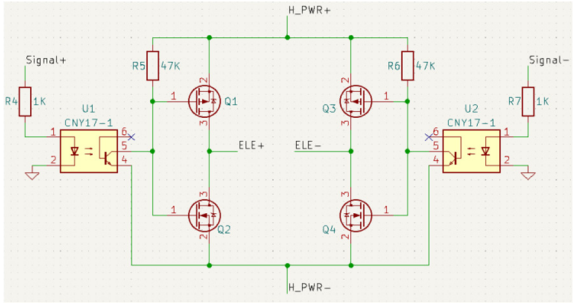

Figure 11: H Bridge circuit developed.

3.2.3 PCB Layout and Properties

As far as the layout is concerned, all the rules required by the component datasheets were considered, and the result is shown in Figure 12.

Note that the components are only in the upper part, with the lower part only containing the battery connector.

Looking at Figure 12 one can see:

- *Purple (1):* USB type-C connector, charging circuit and selector switch for disconnecting the battery from the charger or from the circuit.
- *Red (2):* ESP32 with regulator and surrounding circuitry (enable pin, boot pin, etc.).
- *Orange (3):* 3.7V battery to 5V converter.
- *Blue (4):* Converter from 5V to 45V, with potentiometer for adjusting the output voltage.
- *Green (5):* Current limiting circuit, with potentiometer for adjusting the maximum current.
- *Yellow (6):* H-bridge circuit with output for the electrodes.

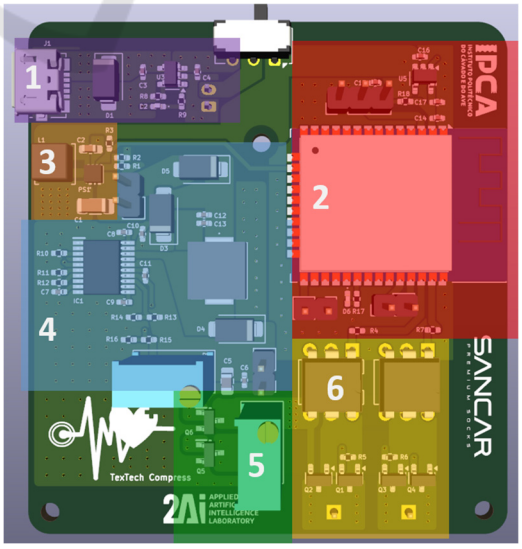

Figure 12: *PCB layout by blocks.*

Table 1 presents the final specifications of the module.

Table 1: Specifications of the developed module.

Specification	Value
Charging voltage	5V
Output voltage	45V
Battery voltage	3.7V
Maximum output current	20mA
Operating frequency	1 – 100 Hz
Pulse width	50 uS – 100 uS
Signal type	Two-phase square wave

3.3 Software

As previously referred the mobile application was developed to act as a remote control for the electrostimulation system. It includes the following characteristics:

- Connecting to a Bluetooth Low Energy device.
- Creation of a new electrostimulation session.
- Add electrostimulation programmes to the session.
- Edit electrostimulation session programs.
- Start and pause the electrostimulation session.

As referred, BLE was used for communication between the stimulation module and the Smartphone (Bluetooth Special Interest Group, 2023), which is the most widely used communication in wearable health devices. In this work, a service was created with four characteristics:

- *IsRunning* – Indicates if a treatment session is in progress.
- *RemainingTime* – Indicates the time remaining until the end of the treatment session in seconds.
- *SendProgram* – Characteristic where the treatment session is sent from the Smartphone to the electrostimulation module.
- *StopProgram* – Sending a message to stop the session.

The mobile application was developed in .NET MAUI (Microsoft, 2024). Figure 13 shows the 'treatment session' pages, which contains the session created by the user and then sent to the module (Figure 13 left).

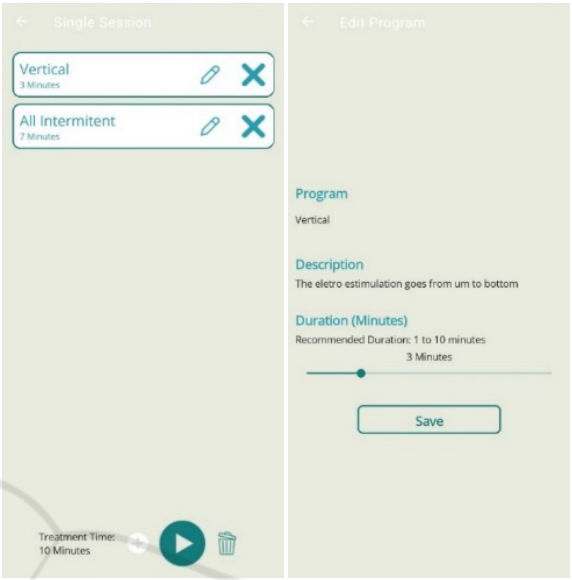

Figure 13: Left: Treatment edition page. Right: Treatment session page.

In Figure 13 right one can see the page for selecting the programme to add to the treatment session, as well as the duration of the session. It also integrates brief information about the purpose of the programme to be added.

The application currently has six programs to be added to the treatment session, as shown in Table 2. What differs between the programs is the frequency, pulse length and activation and pause times.

By selecting the program for the electrostimulation session, the user also sets the duration.

As the programs are stored in the application, new programs can be added in the future without having to change the module's firmware.

Table 2: Electrostimulation programs available on the mobile application.

Program	Frequency (Hz)	Pulse length(µsecs)	Activation time(sec)	Pause time(sec)
Train	90	60	1	1
Knead	10	100	2	2
Massage Low Frequency	10	100	2	1
Massage High Frequency	100	50	4	4
Activation Low Frequency	30	100	2	2
Activation High Frequency	90	60	2	2

4 DEVICE FUNCTIONING RESULTS

Once the layout had been concluded, the assembly and respective tests were carried out.

During the tests, the two-phase electrical signal was validated, as well as the current limitation, since when the skin was short-circuited, the voltage remained stable. Sensitivity was also validated on the skin with gel pads specific for electrostimulation devices. Figure 14 shows the assembled PCB.

Figure 14: Assembled portable PCB.

In Figure 15 one can see the result of a test involving biphasic pulses at a frequency of 100Hz, without the pad being in contact with human skin.

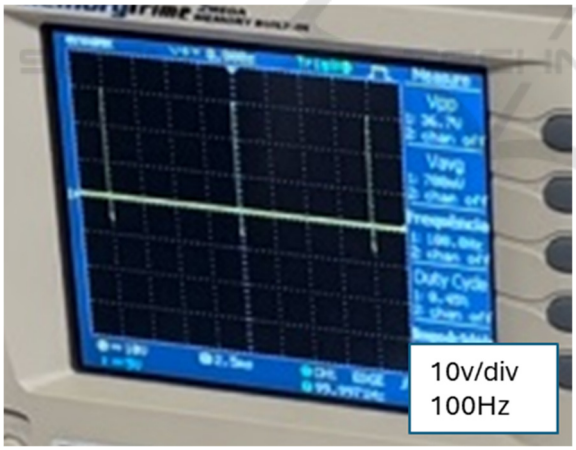

Figure 15: Biphasic pulse at 100Hz.

In Figure 16 one can see the result of another test at a frequency of 2Hz, now with skin contact, where a small amount of expected distortion can be observed.

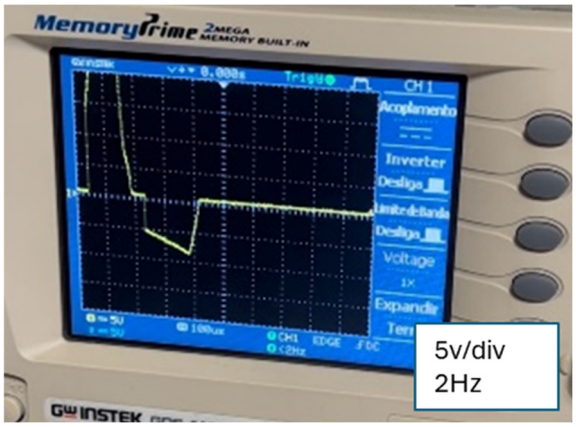

Figure 16: Biphasic pulse at 2 Hz.

In Figure 17, we can see the device being charged via USB-C, with the LED signalling charging in progress.

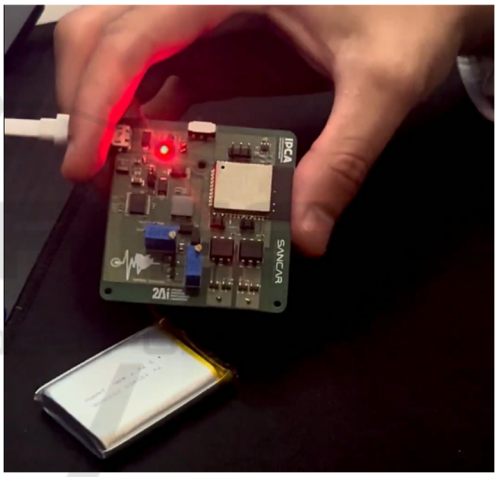

Figure 17: Charging the device.

In Figure 18 left, one can see an example of an electrostimulation session in progress and the application indicating the time remaining. In Figure 18 right, one can see the module running the electrostimulation session, with the pad in contact with the skin.

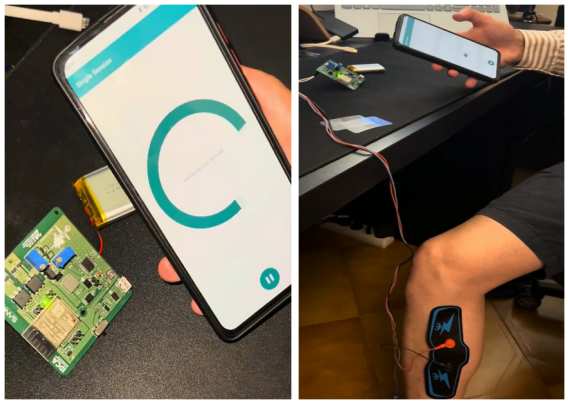

Figure 18: Left: Electrostimulation session in progress. Right: Module in operation.

After validating the electronics, we moved on to the development of the casing and its integration in the designed compression socks.

The following considerations were considered when developing the casing and compression socks:

- The module must be easily removable so that the socks can be washed.
- The electrical pulse from the device to each muscle must be conducted using textile conductive threads.

For this reason, a prototype of the compression sock was built, in which the electrical pulse is conducted through a silver-plated yarn. Magnetic snaps were placed at the contact points to attach the module to the socks, as well as the medical pads for electro-stimulation.

Figure 19 shows the outer part, with the magnetic snaps that will allow contact with the module and the *pads*, as well as the silver-plated conductive yarns.

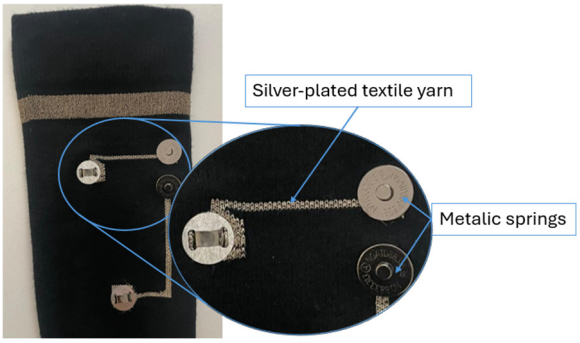

Figure 19: Outside of the compression socks.

Figure 20 shows the inside of the socks, which has been insulated to prevent the conductive yarn from coming into contact with the skin, making it possible only at the specific points of the muscle, where the medical pad is inserted.

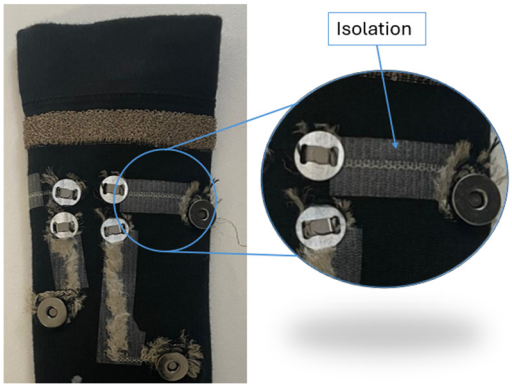

Figure 20: Inside of the compression socks.

Tests were carried out to validate the electrical conduction of the textile, as well as the sensitivity of the pulse on human skin.

Figure 21 shows confirmation of the textile's conduction.

Figure 21: Electrical conductivity tests on textile.

Figure 22 shows the sensitivity tests on human skin, thus validating the functioning of the developed product.

Figure 22: Final working prototype in a human.

This resulted in the final prototype shown in Figure 23.

Figure 23: Final prototype

5 CONCLUSION AND FUTURE WORK

In conclusion, all the objectives of this research have been successfully achieved. A proof of concept has been developed for a wireless electrostimulation device, controlled via a smartphone application. This device can be connected to socks with specific characteristics that conduct electric current to targeted areas of the lower legs, thereby enhancing blood flow through muscle activation.

During the development process, several challenges were encountered, such as the issue of accurately sensing the electrical pulse. This led to an in-depth investigation into the problem, ultimately resulting in a clear understanding and an effective solution.

The Bluetooth Low Energy (BLE) communication between the smartphone and the module, as well as the electrical signal delivery to the electrodes, have been thoroughly validated and confirmed to be operational. The mobile application has been successfully compiled and tested on various Android devices, ensuring compatibility across different Android versions. Although testing in an iOS environment was not conducted, it is feasible to compile the application on iOS using a development account and an Apple device, without needing to modify the core code.

In terms of electrical improvements, we identified the potential for enhancing pulse modulation, which is currently generated exclusively by hardware, and current control, which is managed using digital potentiometers.

From a firmware perspective, further improvements could be made in battery management, such as implementing a sleep mode for the ESP32 when no treatment session is in progress, to optimize power consumption.

Finally, the software component of the system offers several opportunities for enhancement. The current mobile application is functional, but its user interface could be further refined for better aesthetic appeal and user experience. The application was initially developed to demonstrate the system's functionality and control mechanisms, leaving room for design improvements. Compared to other equipment on the market, this meets the technical specifications for EMS equipment and is a good basis for a commercial version.

Taking advantage of the interactivity between the device and the smartphone, a potential extension of this solution, we propose the development of an online treatment platform that would allow healthcare professionals, such as doctors and physiotherapists, to remotely monitor and manage users' treatment sessions.

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