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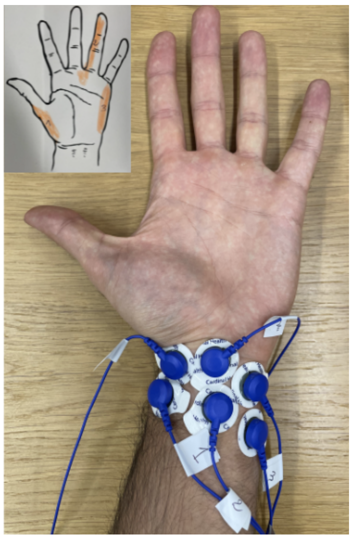
Controller for targeted transcutaneous electrical nerve stimulation (tTENS) to non-invasively provide tactile sensory feedback for non-disabled subjects

Semester Project



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[1] E.g. ChatGPT, DALL E 2, Google Bard
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Abstract

This report presents the development and evaluation of a platform for conducting psychophysical experiments using Targeted Transcutaneous Electrical Nerve Stimulation (tTENS) with the goal of providing multi-channel sensory feedback for prosthetics and Virtual Reality (VR) applications. The project focuses on addressing challenges in psychophysics, including the determination of minimum detection and maximum stimulation thresholds. Pilot tests were conducted on two subjects to validate the experimental protocol, revealing critical factors such as inter-subject variability, the influence of wrist posture, and the consistency of referred sensations during calibration.

The adaptive staircase method was implemented to efficiently estimate thresholds. The findings emphasize the importance of optimizing electrode placement, refining stimulation protocols, and compensating for wrist movements to improve the accuracy and reliability of the results. Additionally, the project highlights the limitations of constant step size strategies for high-intensity stimulation, advocating for the integration of advanced adaptive methods.

This work establishes a foundation for future research into tTENS-based sensory feedback systems, offering pathways for exploring electrode design, nerve-stimulation relationships, and applications in both prosthetics and VR. By addressing the challenges identified, the platform has the potential to advance non-invasive sensory feedback technologies, contributing to more natural and reliable human-machine interfaces.

Contents

List of Figures

List of Tables

List of Acronyms

2AFC . . . . . . Two-Alternative Forced Choice

API . . . . Application Programming Interface

DAC . . . . Digital to Analog Converter

GUI . . . . Graphical User Interface

INI . . . . Institute of Neuroinformatics

JHU . . . . Johns Hopkins University

JND . . . . Just Noticeable Difference

TENS . . . . . . Transcutaneous Electrical Nerve Stimulation

tTENS . . . . . Targeted Transcutaneous Electrical Nerve Stimulation

VR . . . . Virtual Reality

Chapter 1

Introduction

1.1. Motivation

Neuromorphic technology, inspired by the intricate behavior of biological neurons and synapses, offers an unparalleled opportunity to bridge the gap between artificial systems and the natural encoding of touch. This approach addresses critical challenges in tactile sensory systems, including limitations in bandwidth—both in the frequency range of acquired data and in the scalability of high-density receptor arrays. By replicating the biological efficiency of natural sensory encoding, neuromorphic designs have the potential to revolutionize sensory feedback systems.

However, for these advancements to translate into practical applications, they must be coupled with neural interfaces capable of handling high-bandwidth data streams while maintaining selective and precise stimulation. Among the emerging technologies, biphasic tTENS has shown significant promise as a non-invasive and versatile neural interface. Despite its potential, the full capabilities of tTENS remain underexplored, with recent studies beginning to uncover its ability to elicit targeted tactile feedback[2][3].

The non-invasive nature of tTENS confers numerous advantages over invasive approaches, including reduced risk of complications, greater ease of use, and the elimination of surgical procedures. Furthermore, the technology can be engineered to be portable, enabling on-the-go applications in both medical and non-medical domains. This portability, combined with its potential for cost-effectiveness, positions tTENS as a practical solution not only for advanced prosthetics and rehabilitation in individuals with limb loss but also for immersive applications in virtual reality (VR) and gaming.

In medical settings, tTENS holds the promise of enhancing the quality of life for amputees by restoring tactile sensations critical for interaction with their environment. Beyond healthcare, its ability to provide high-fidelity sensory feedback opens the door to innovations in human-computer interfaces, offering more immersive VR experiences and realistic haptic feedback in gaming. The development and optimization of tTENS technology thus represent a critical step toward bridging the gap between biological sensation and artificial systems, paving the way for next-generation neuroprosthetics and interactive systems.

1.2. Objective

The primary objective of this work is to develop a hardware/software platform to flexibly generate TENS patterns and design psychophysics experiments. A Digitimer DS8R [1] TENS unit and D188 [4] Electrode selector had already been procured before the start of this project. The goal is to leverage the bi-phasic stimulation and multi-channel capabilities of these two devices to further investigate the use of tTENS as a viable method for sensory feedback.

The broader goal is to evaluate how tTENS can be combined with neuromorphic technologies to emulate natural tactile sensations more effectively.

This project also marks the beginning of a new collaboration between Institute of Neuroinformatics (INI) and Johns Hopkins University (JHU). The tools and methodologies developed during this work are intended to serve as a shared resource for both laboratories

Chapter 2

Hardware Setup

2.1. Block diagram

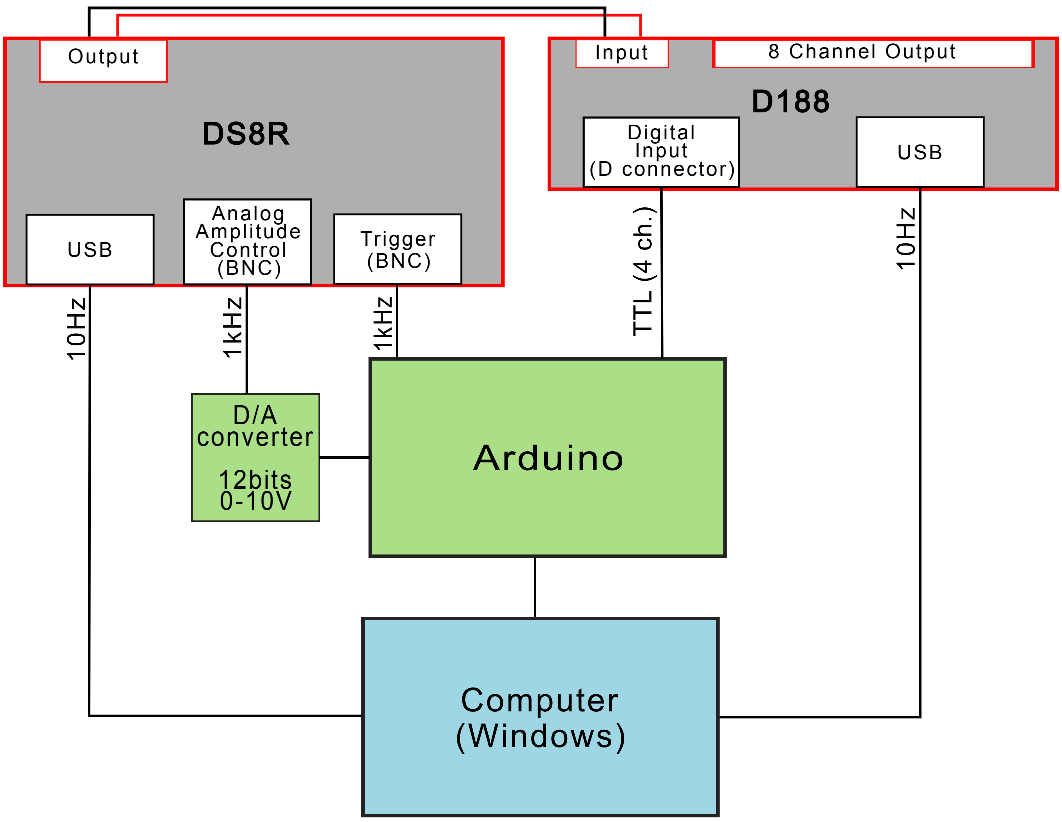


Figure 2.1.: Setup Block Diagram.

2.1.1. Digitimer Instruments

The Digitimer DS8R stimulator [1] and the D188 Electrode Selector [4] were selected by Elisa Donati in consultation with the JHU group, who had prior experience conducting psychophysics TENS experiments. One of the objectives of this project was to evaluate the capabilities and limitations of these devices to facilitate the effective design of psychophysics experiments. Additionally, this evaluation aimed to ensure compatibility with a neuromorphic chip, enabling future advancements in sensory feedback systems.

2.1.2. Microcontroller and D/A Converter

An Arduino 101 (Intel® Curie™) was used as an interface between the computer and the Digitimer instruments, as shown in Figure 2.1. This setup enabled the system to achieve the maximum triggering and pulse amplitude modulation frequencies of 1 kHz and the minimum channel switching interval of 1 ms, which were only possible using the BNC connectors and Digital Input Socket on the back panel of the devices. This particular microcontroller was chosen because it was readily available in the lab and, when combined with the Terminal Block Shield (DFR0920), it offered an effective wire management solution.

A Digital to Analog Converter (DAC) (Gravity: 2-Channel I2C DAC Module, 0–10V, 12-Bit) was purchased to interface the Arduino with the DS8R external amplitude control input via the BNC socket on the back panel. This input accepts a voltage range of 0–10V and maps it linearly to the output current amplitude, with a range of [0–Locked Current Amplitude]. The locked current amplitude is set manually on the front panel of the DS8R and represents the maximum permissible current amplitude, regardless of the software request.

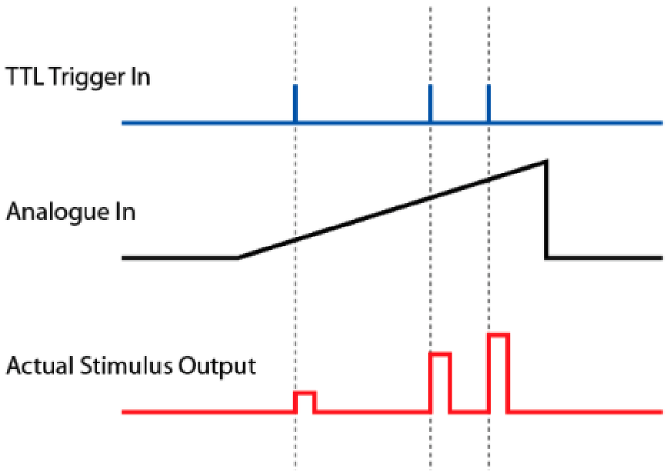


Figure 2.2.: External Amplitude Control. (Source: [1])

Current Amplitude Accuracy:

First, The DAC module has an output voltage error less than 0.5%. Second, the external amplitude control accuracy, i.e the voltage-to-current converter, is given as a fixed value of ±1 mA. We can assume a "Locked Current Amplitude" of 100 mA which was never reached during the pilot experiments and can be considered a worst case scenario to deduce $E_{\mathrm{V2I}} = 1\%$. Finally, the DS8R current output has an accuracy of 2%. This means, a set current of 10.0 mA will be 10 mA ± 0.2 mA and a set current of 100 mA will be 100 mA ± 2 mA. The total root mean square (RMS) error of the system can therefore be calculated as:

$$E_{\mathrm{total,rms}} = \sqrt{(E_{\mathrm{DAC}})^2 + (E_{\mathrm{V2I}})^2 + (E_{\mathrm{output}})^2} = \sqrt{(0.5\%)^2 + (1\%)^2 + (2\%)^2} = 2.29\%$$

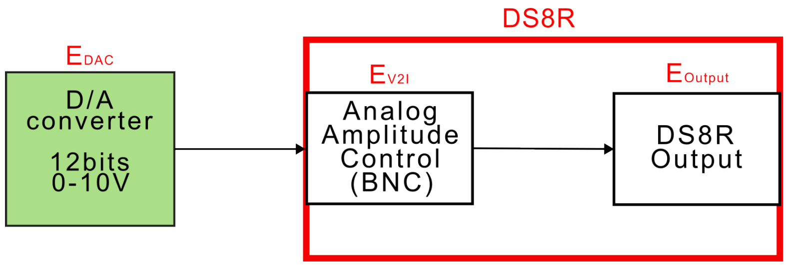


Figure 2.3.: Block diagram showing the current amplitude error propagation path in the system

Resolution

The DS8R has a step size of 0.1 mA. Notably, the output error of 2% exceeds the step size for current amplitudes greater than 5 mA. The DAC has a 12-Bit resolution with a 0–10 V output range, resulting in a theoretical voltage resolution calculated as:

$$\text{Resolution} = \frac{\text{Full Scale Range}}{2^N} = \frac{10V}{2^{12}} = 2.44mV$$

When applied to a "Locked Current Amplitude" of 100 mA, this corresponds to a current resolution of 0.024 mA.

2.1.3. Laptop Requirements and USB Configuration

The laptop requires at least three USB ports: two for the Digitimer instruments and one for the microcontroller. Even if the microcontroller is used to trigger, modulate the amplitude, and switch channels, it is still necessary to connect the instruments via USB to set them to the correct mode. For instance, the D188 must be set to 4TTL mode, and the DS8R requires configuration of the pulse shape.

Note: The purchased USB hub was relatively inexpensive, and investing in a higher-quality hub may be beneficial in the future. Currently, only two USB connections are routed through the hub, with the third connected directly to the laptop. It is suspected that the hub may be causing malfunctions when all three USBs are connected simultaneously.

2.2. Electrode Selection

The type of electrodes used plays a crucial role in shaping the induced sensation and will be a key optimization parameter in future work to achieve a more natural and reliable tactile experience.

While invasive approaches can directly target specific nerves, tTENS seeks to stimulate peripheral nerves by precisely positioning each pair of electrodes to create effective charge pathways. This process is further refined by altering stimulation patterns to account for variations in nerve site and depth, skin conductance, and other factors that remain poorly understood.

The channels of the D188 electrode selector utilize 1.5 mm DIN 42802 touch-proof connectors. This standard, commonly used in medical and biomedical recording systems, became widely adopted following regulatory requirements for insulated connectors in clinical settings, as outlined in IEC 60601-1.

To establish criteria for selecting surface electrodes for this project, a literature review was conducted to assess commonly used electrodes in previous studies (Table 2.1). Many of these studies focus on TENS as a method for pain relief. Although TENS for pain relief shares the same underlying stimulation method as tTENS for somatosensory feedback, the specificity requirements differ. Pain relief applications typically employ large electrodes, such as PALS electrodes, which prioritize comfort and flexibility over precision.

Author	**Paper**	**Electrodes used**
L. Osborn et al.	Targeted transcutaneous electrical nerve stimulation for phantom limb sensory feedback [2]	Ag-AgCl probe with a 2 mm tip for mapping and 5 mm disposable Ag-AgCl electrode for calibration
L. Osborn et al.	Phantom hand activation during physical touch and targeted transcutaneous electrical nerve stimulation [3]	1 mm beryllium copper (BeCu) probe for mapping
L. Osborn et al.	Sensory stimulation enhances phantom limb perception and movement decoding [5]	monopolar 1 mm beryllium copper (BeCu) probe for mapping and 5 mm disposable Ag/AgCl electrodes for calibration (Norotrode 20, Myotronics, USA)
M.A. Trout et al.	A portable, programmable, multichannel stimulator with high compliance voltage for noninvasive neural stimulation of motor and sensory nerves in humans [6]	The stimulation pad was a 9-cm2 square pad, 4-mm thick, and consisted of one 0.79-cm2 (1 cm diameter) stimulating electrode surrounded by four 0.44-cm2 (0.75 cm diameter) ground electrodes.
T. R. Benigini et al.	Simultaneous modulation of pulse charge and burst period elicits two differentiable referred sensations [7]	self-adhesive gel electrodes, two 15 mm by 20 mm stimulating electrodes and two 20 mm by 25 mm return electrodes (Rhythmlink International LLC, Columbia, SC, STCUL15026, and STCUS25026)
X. Bao et al.	Electrode placement on the forearm for selective stimulation of finger extension/ flexion [7]	Round hydrogel electrodes, 2.2 cm in diameter, were used as the negative electrodes, and rectangular hydrogel electrodes of 4×4 cm were used as the positive electrode.

Table 2.1.: Collection of electrodes used in tTENS literature

Chapter 3

Control Software

Custom software was developed during this project to control the instruments and create the psychophysical experiments. The software is hosted on the INI GitLab, with the repository containing detailed documentation, source code, and instructions for setup and usage. The primary components of the work include:

- **API Integration**: The original Digitimer API was provided as a DLL library that required another layer to interface with it. Dedicated controllers for the Digitimer DS8R stimulator and D188 electrode selector facilitate seamless communication and allow parameter adjustments via predefined commands.
- **Graphical User Interface (GUI)**: Developed using Qt, the GUI helps the experimenter easily perform the mapping step by giving him full controll over all instuments and provides an interface for the subject to interact with during the experiments.
- **Automation Scripts**: Python-based scripts automate the generation of stimulation patterns allowing for advanced calibration strategies and reliable data acquisition.

The control software's modular design ensures extensibility, enabling future adaptations for more complex experiments. It also features error-handling routines to enhance robustness during long experimental sessions.

For detailed instructions on installation, usage instructions, and troubleshooting, refer to the GitLab repository under the project name `tTENS`.

Chapter 4

Methods

4.1. Psychophysics for tTENS

Psychophysics is the study of quantitative relations between psychological events and physical events or, more specifically, between physical stimuli and the sensations and perceptions they produce.

For this study, stimulation sequences are generated using current-controlled, charge-balanced biphasic rectangular pulses as the fundamental building blocks. Current-controlled stimulation ensures safety by regulating the charge density delivered by each waveform regardless of the impedance at the electrode-skin interface. Furthermore, charge-balanced biphasic pulses reduce discomfort,a common issue associated with noninvasive monophasic stimulation or excessive charge density [8][9][6].

tTENS may require simplifying neuromorphic encoding to accommodate the capabilities of the stimulator. Nonetheless, one of the primary challenges with tTENS is the wide space of parameters that can be varied, whose effects remain poorly understood and are prone to inter-subject variability. Due to this, psychophysics experiments can extend over several hours, making smart parameter exploration strategies critical to ensure efficiency and meaningful outcomes.

With the DS8R current stimulator, the shortest biphasic pulse that can be generated is 101 µs (50 µs first pulse duration + 1 µs interphase duration + 50 µs second opposite sign pulse duration) which corresponds to a theoretical maximum stimulation frequency on a single channel and without parameter modulation of about 9900 Hz. The D188 Electrode selector has a minimum switching interval of 1 ms allowing for switching between different channels at a frequency of up to 1 kHz. The parameters that can be varied include trigger frequency, pulse amplitude, pulse width, interphase interval and recovery phase ratio. The recovery phase ratio is expressed as a percentage of the first pulse amplitude, with the recovery phase duration adjusted to maintain charge balance. Refer to Table 4.1 for the parameter ranges that can be generated.

Parameter	**range**	**step**
Frequency	1/pulse_duration	N/A
Pulse amplitude	0–1000mA	0.1mA
Pulse Duration	50–2000µs	10µs
Interphase interval	1–990µs	10µs
Recovery phase ratio	10–100%	1%

Table 4.1.: TENS Modulation Parameters

4.1.1. Reducing The Parameter Space

To design psychophysics experiment sessions of reasonable duration, the parameter ranges to be explored were constrained. The way selection was done was based on the final desired application, which is real time multi-channel sensory feedback on a prosthesis or VR bracelet with high bandwidth.

The Digitimer DS8R stimulator has an external trigger input that allows triggering at any desired frequency, provided the pulses do not overlap. The external analog amplitude control input responds to amplitude changes at a maximum frequency of 1 kHz (lag = 1 ms). All other parameters can only be set using the USB connection, which has a maximum frequency of 10 Hz.

These hardware limitations make frequency and pulse amplitude the only parameters with sufficient bandwidth for use as haptic feedback variables. Consequently for this project, the pulse width was fixed at its minimum value of 50 µs. The interphase interval was set to 10 µs and the recovery phase ratio was set to 75% yielding a recovery phase of 66.6 µs. This configuration leverages the benefits of a biphasic waveform while keeping the total pulse duration short. The resulting total pulse duration is 126.6 µs , corresponding to a frequency of 7898 Hz.

The triggering frequency was set to 15 Hz to have a continuous sensation.

4.2. Calibration Methods

4.2.1. Classical psychophysical methods

Method of constant stimuli

This is arguably the most commonly employed method in the literature about tTENS[2]. It consists in randomizing the stimuli levels that are presented to the subject to prevent them from predicting the next stimulus. It also allows for full sampling of the psychometric function which is fit with a sigmoid link function. Conventionally, the detection threshold is defined as the stimulus level corresponding to a probability of P(yes)=0.5. However, in practical applications, this threshold may not ensure reliable detection.

Method of limit

The ascending method of limit consists in starting from a stimulus that is not detectable by the subject and incrementing the stimulus until the subject reports feeling something. The descending method is reversed. Usually the ascending and descending methods are alternated and the threshold is the average of all trials. This method is prone to adaptation and subjects may try to predict the next stimulus. The staircase method explained later is an improved version of the method of limit that is less vulnerable to these potential issues.

Method of adjustment

This method consist of setting the stimulus intensity above or below the threshold and letting the subject "tune" the stimulus intensity himself until it is perceptible or until it reaches a reference stimulus. This method is the quickest and can be performed easily with DS8R stimulator directly.

4.2.2. Adaptive psychophysical methods

Adaptive methods aim to improve efficiency by collecting data points primarily in the region of interest, typically near the threshold.

Staircase method

This method can start from a perceivable or non-perceivable stimulus. If it starts from a perceivable stimulus, then the intensity is decremented until the subject reports not feeling anything which triggers a reversal of the staircase and the stimulus is incremented until the subject reports feeling something. The detection threshold is estimated by averaging the final three inversion points. The staircase algorithms can also vary the step-sizes and inversion rules. This method was implemented in this project.

Maximum-likelihood and Bayesian method

In this method the decision of the next stimulus is based on all past data points. From all the saved stimulus/response pairs, the point of maximum likelihood of where the threshold lies is calculated and assigned as the next stimulus. In Bayesian procedure, the previous likelihood is also taken into account. Multiple algorithms exist for this procedure, including QUEST, ML-PEST, and the method proposed by Kontsevich and Tyler. The maximum-likelihood and Bayesian method is the most robust between the ones mentioned in this section, but is more time consuming to implement [10].

4.2.3. Chosen calibration method

The staircase method was selected for its balance of efficiency, robustness, and feasibility within the project's time frame. The number of inversion points, also referred to as the number of reversals, was chosen to ensure the experiment duration remained reasonable while still collecting sufficient data points for the curves to converge and oscillate around a stable value. The detection threshold was calculated as the median of the inversion points, ensuring robustness against outliers.

Chapter 5

Results

Within the project time frame, only pilot tests were performed. The significance of the results of these tests is limited due to errors caused by inexperience in conducting psychophysics experiments. Nonetheless, many valuable lessons were learned that will be summarized in this section.

Psychophysics experiments were performed on two subjects. Subject A, a male, was tested on the left arm, and Subject B, a female, was also tested on the left arm. The experimental protocol consisted of two main steps: a mapping step and a calibration step, which included determining the minimum detection thresholds and maximum stimulation threshold.

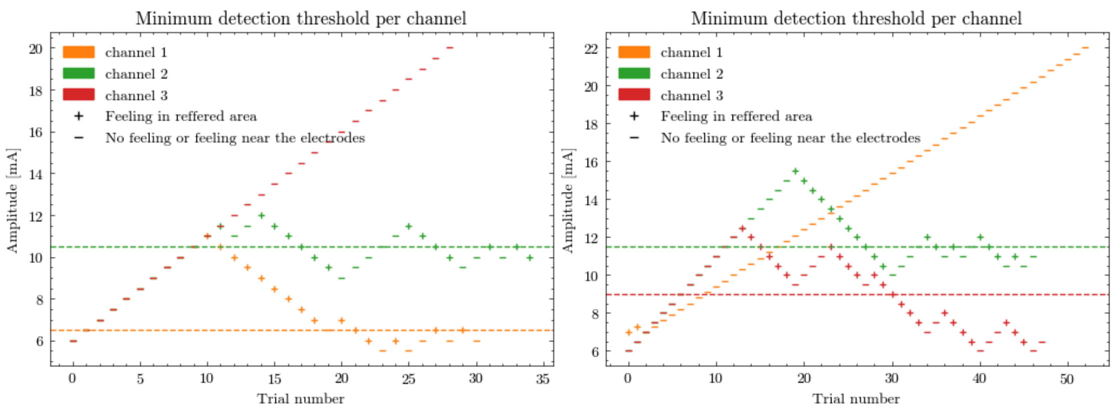
Subject A participated in two sessions, each beginning with the mapping step, followed by the one calibration step. Subject B participated in a single session, which started with the mapping step and was followed by the two calibration experiments conducted consecutively.

5.1. Minimum Detection Threshold Experiment

Minimum detection threshold experiments were conducted on two subjects using the adaptive staircase method. Stimulation parameters (Table 5.1) were configured based on the analysis presented in the Methods chapter.

Parameter	**Value**
Frequency	15Hz
Pulse amplitude	**variable**
Pulse Duration	50µs
Interphase interval	10µs
Recovery phase ratio	75%
Stimulation duration	1s
Number of inversion points	10
Polarity	Negative
Mode	Biphasic

Table 5.1.: Experiment Parameters



(a) Subject A (b) Subject B

Figure 5.1.: Minimum detection thresholds for subjects A and B, measured across three stimulation areas per subject. Pulse amplitude was modulated for each channel individually, with the stimulation frequency fixed at 15 Hz. The detection thresholds, calculated as the median of the inversion points, were 6.5 mA and 10.5 mA for channels 1 and 2 of subject A, and 11.5 mA and 9 mA for channels 2 and 3 of subject B. In channel 3 for subject A and channel 1 for subject B, the referred sensations identified during the mapping step were not reproducible during calibration.

In Fig.5.1, the threshold was defined as the median of the inversion points to minimize the impact of initial large variations. Some methods in the literature calculate the threshold by averaging the value of the last three inversion points which leads to a similar result.

During the pilot tests, subjects were asked to respond to two questions: The first question was "Do you feel something?" with a Yes/No response, and the second was "Where do you feel it?" with three possible responses: "Near the electrodes," "In the referred area," or "Both." The plus signs in Fig.5.1 correspond to a "Yes" for the first question and "In the referred area" for the second question.

However, this two-question approach was modified after the pilot tests. First, it became evident that the referred sensation may not always be perfectly perceived during calibration. This was observed in channel 3 for subject A and channel 1 for subject B. Although a point eliciting a distal percept was identified during the mapping step using the probe, the referred sensation was inconsistently felt during calibration. Subjects either reported the sensation both near the electrodes and in the referred area, or only near the electrodes.

After these observations, the two questions were combined into a single question: "Do you feel something?" with two response options: "Yes (in referred area)" or "No". This change was made with the agreement that it will be acceptable if the subject feels the sensation both near the electrodes and in the referred area, given the inherent difficulty in achieving perfect stimulation.

Each staircase sequence was conducted independently for each channel, without shuffling between channels, to simplify testing of the method. Once the methodology is validated, future experiments could explore shuffling between channels to mitigate discomfort, skin irritation, and adaptation.

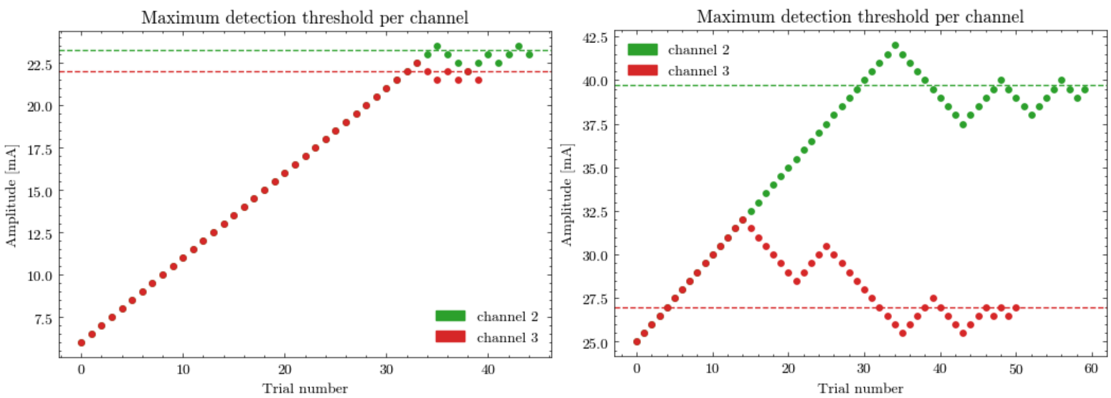
5.2. Maximum stimulation threshold experiment

The maximum stimulation threshold experiment aimed to determine the upper limit of pulse amplitude that could be reached during modulation.

The threshold, shown in Fig.5.2, was initially determined based on the subject's reported pain level. After each stimulation, the subject was asked to rate their pain on a scale from 0 to 10, where 0 represented no pain and 10 represented the worst imaginable pain. A pain level of 7 was arbitrarily chosen as the threshold for discomfort, triggering the inversion points in the stimulation algorithm. However, this method was deemed inadequate after the pilot tests. Pain tolerance and the subjective interpretation of a "level 7" pain rating varied significantly between subjects, making the method unreliable for determining the upper stimulation range.

Following the pilot tests, the protocol was revised to use a Two-Alternative Forced Choice (2AFC) question "Is it comfortable?" with a "Yes" of "No" response, providing a more consistent and interpretable measure of the threshold.

Channels where the referred sensation identified during mapping was lost during calibration could not be tested for maximum stimulation thresholds. High-charge stimulation in these channels resulted only in an uncomfortable sensation near the electrodes, rendering further exploration unfeasible.



(a) Subject A (b) Subject B

Figure 5.2.: Maximum stimulation threshold for subject A and B based on pain level. Each subject had 2 stimulation areas. Pulse amplitude was modulated for each channel separately and stimulation frequency was set at 15Hz. From the median of the inversion points, subject A had a maximum stimulation threshold of 23.25mA and 22mA for channel 2 and 3 respectively and subject B had a threshold of 39.75mA and 27mA for channel 2 and 3 respectively.

Chapter 6

Discussion

The pilot experiments highlighted several challenges and limitations that require attention to improve future psychophysical studies. First, the experiment questions were interpreted differently among subjects, emphasizing the need for more standardized phrasing. Ideally, questions should follow a 2AFC format and be pre-tested with a diverse group to ensure consistent understanding across participants. Second, wrist posture significantly influenced the perception of stimulation, due to forearm movements shifting underlying nerve positions [11]. A fixed wrist position should be established for all experiments to minimize variability caused by muscle activity.

Additionally, electrode placement emerged as a key factor affecting the consistency and the quality of referred sensations during calibration. Current electrodes are relatively large causing variability in sensation between the mapping and calibration and how many electrodes can be packed on the wrist. Moreover, issues such as skin irritation and discomfort became more pronounced during prolonged testing sessions, especially at higher charge densities, highlighting the importance of refined experimental protocols.

The maximum stimulation threshold experiments also present unique challenges due to the complex interplay of physiological and perceptual factors. First, a gradual ramp-up in stimulation intensity is critical to prevent overshooting the subject's comfortable limit, which is unknown at the outset and varies greatly across stimulation areas and between subjects. Second, higher charge levels exacerbate issues such as skin irritation and adaptation, reducing the subject's tolerance and potentially influencing threshold determination. Third, as described by the Weber–Fechner law, the Just Noticeable Difference (JND)—the minimum detectable change in stimulus intensity—rises with increasing pulse amplitude. This phenomenon renders strategies using constant step sizes both inefficient and more susceptible to subject adaptation, underscoring the need for adaptive methods tailored to high-intensity stimulation.

Chapter 7

Conclusion

This semester project laid the groundwork for conducting psychophysical experiments using tTENS and established a robust platform for further research. The project successfully demonstrated the feasibility of employing adaptive methods for threshold estimation and identified key areas for improvement in experimental design.

The outcomes of this work open pathways for several future studies. Investigating alternative electrode designs and placements could enhance the stability and reproducibility of referred sensations. Understanding the relationship between stimulus amplitude and nerve location may improve the precision of stimulation. Strategies to compensate for wrist movements could mitigate variability in perception, ensuring more consistent results. Furthermore, extending the experiments to amputees offers the potential to explore tTENS as a viable approach for sensory feedback in prosthetics.

Ultimately, this project provides a foundation for integrating tTENS with neuromorphic systems, enabling multi-channel stimulation and advancing the development of non-invasive sensory feedback technologies. By addressing the challenges identified in this study, future research can unlock the full potential of tTENS in both clinical and virtual reality applications.

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Appendix A

GitLab Repository

Code, user instructions and further explanations can be found on the INI GitLab under project tTENS.

```
tTENS
├── README .........................................................
├── API ...................... The source files of the instruments control libraries.
│   ├── README ................................... List of available commands.
│   ├── d188_controller ............ Control commands for the electrode selector.
│   └── ds8r_controller .................. Control commands for the stimulator.
├── Arduino ........................... The source code of the microcontroller.
│   └── TENS_controller .............................................
│       └── TENS_controller .........................................
├── QtDesigner ...................... Front-end code for the design of the GUIs.
│   ├── gui_experiment_win2.ui ......... The source code the experiment window.
│   └── gui_mapping.ui ................. The source code of the mapping window.
├── datasheet ......................................... Digitimer documents.
├── images .............................. Images used for the README section.
├── video ................................................... Tutorial video.
├── recorded_data ............................... Automatically recorded data.
├── .gitignore ......................................................
├── plotter ........................ Notebook for plotting the experiment data.
├── script0_mapping ....................... The source code of the mapping step.
├── script1_min_detection_threshold ........... The source code of calibration.
└── script2_max_detection_threshold ........... The source code of calibration.
```

Appendix B

API

B.1. D188 API

Command	**Parameter**	**Description**
`Initialise`	None	Must be the first function called to initialise the D188 stack and return an instance reference.
`SetChannel`	`channel`	Set which channel is active: (int) in [0-8] with zero equivalent to all channels open.
`SetMode`	`mode`	Set which control mode is used for the selector: (string) 'OFF', 'USB', '8TTL', or '4TTL'.
`SetIndicator`	`state`	Set the LED indicators as activated/deactivated: (string) 'ON' or 'OFF'.
`SetDelay`	`delay`	Set the delay/de-bounce setting. `delay (float)`: between 0.1-1000 milliseconds.
`PrintState`	None	Print the current content of the D188 STATE.
`Close`	None	Close and free all resources associated with the instance reference (`apiRef`). Called once D188 has been finished with.

Table B.1.: API control functions for the D188

B.2. DS8R API

Command	Parameter	Description
`Initialise`	None	Must be the first function called to initialise the DS8R stack and return an instance reference.
`Mode`	`mode`	Set the mode: (string) 'Mono-phasic' or 'Bi-phasic'.
`Polarity`	`polarity`	Set the pulse polarity: (string) 'Positive', 'Negative', 'Alternating'.
`Source`	`source`	Set the source for the stimulus amplitude: (string) 'Internal' for USB and front panel or 'External' for analog input in the back of the device.
`Demand`	`amplitude`	Set amplitude. (float): acceptable amplitude in [0-1000] mA with one decimal precision.
`Pulsewidth`	`width`	Set pulsewidth. Width of the first square in case of biphasic. (int): acceptable pulsewidth in [50-2000] µs.
`Dwell`	`interpulse`	Set inter-pulse width. Controls the period between the end of the first square and the start of the recovery square when BI-PHASIC mode is enabled. (int): in [1-990] µs.
`Recovery`	`percentage`	Controls the recovery pulse duration in BI-PHASIC mode. The value is a percentage of the amplitude of the recovery pulse compared to the first pulse.
`Enable`	`enabled`	Control of output enable state. (bool).
`Trigger`	None	Triggers one time. Max trigger at 10Hz using USB, otherwise can have bugs.
`Status`	None	Get the current state of the device.
`PrintState`	None	Print the current content of the DS8R STATE.
`Cmd`	`command, *args`	A dispatcher function for calling the previous functions. `command` is a string ('Mode', 'Polarity', etc.), and `*args` respects the previous requirements.
`Close`	None	Close and free all resources associated with the instance reference (`apiRef`). Called once DS8R has been finished with.

Table B.2.: API control functions for the DS8R