Decrease in Perception Threshold of Electrocutaneous Stimulation by changing Stimulation Parameters

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***Abstract*—The long-term goal of this research is to improve the perceived feeling from electrocutaneous stimulation used for neural prostheses. The prevalence of spinal cord injuries (SCI) is estimated to be 755 per million people per year. Similarly, the number of people living with amputations was 1.6 million in 2005. Both estimates are expected to increase, or even double, in the upcoming years. Some current upper limb prosthetics contain haptic feedback, which allow users a more "closed loop" system, but still have many issues in their accuracy and reliability. There is a need for more accurate stimulation feedback in order to improve the usability of the devices and to decrease rejection. To help address this, we explored electrode placement and Pulse Width modulation as possible parameters that could increase sensation while keeping stimulation low. We identified that i) the location of the electrodes has a significant impact on the perception threshold; ii) Pulse Width modulation has less variation in sensation; and iii) the preferred sensation comes from a combination of current modulation and optimal location. These findings have the ability to reduce the visual load of using a prosthetic and provide tactical sensation to amputees, which would decrease rejection from users. It can also provide virtual reality sensation to aid in different therapeutic protocols.**

***Index Terms*—electrocutaneous stimulation, Haptic feedback**

I. Introduction

In 2005, there were over 250,000 people living with a SCI, which can range from still having mobility to tetraplegia [1]. To go along with this, over 80% of amputations are caused by trauma, making them a sudden and severe ailment [2].The adjustment from biological arm use to prosthetic use is sudden, and not made easy with the current systems. A major problem with current prosthetics is the grip strength; it is either too strong and crushes objects, or too weak and drops them [3].

Electrocutaneous stimulation, which stimulates nerves through contact with the skin, is one of the most feasible techniques for generating nerve activity because it is noninvasive and can produce varying levels of sensation that can be reliably controlled [4]. In order to measure the relating electrical signals, an oscilloscope is used, which quantifies the stimulus across the skin using a waveform [5].

Recent work has started to introduce haptic feedback into prosthetic systems, such as Neuromuscular Electrical Stimulation (NMES). This provides a small shock to the user to provide feedback in a video game scenario [3]. Work has also been done on skin stretching devices for proprioceptive sensing by rotational stretching skin in order to more naturally signal arm rotation [3]. Both of these approaches seem very promising, but also very expensive and involve time consuming training and familiarization with the technique.

In this paper, we aimed to identify the optimal parameter selection to illicit sensation while keeping the stimulation low. We considered two approaches: i) Pulse width modulation with low current amplitude and ii) electrode location. We followed the basic steps from *Geng et. al*, but made adjustments by using only a single channel of stimulation to lower cost and increase accessibility. We also adjusted the parameters explored to understand what has more of an impact on sensation: location or changes in electrical signal. We found that the location lowered the perception threshold significantly and allowed for more variation in the sensation by using current modulation. We also found that changing the Pulse Width did not have a significant impact on the sensation and was not preferred by the participants.

II. Methods

A. Participants

Four human subjects participated in this study, with 100% being female and ranging in age from 22-28. All participants were healthy, intact individuals with no neurological impairments.

B. Stimulation Hardware

To deliver the simulations, a 1 channel, high voltage stim box was used. This consisted of an Arduino Uno with a top shield. The compliance voltage of the stim box was 15V. The waveforms shown in figure 2 were created using an oscilloscope. The electrodes used were medi trace, 3.6cm diameter electrodes. The electrodes were placed on the ventral wrist crease, and the medial cutaneous nerve of the forearm.

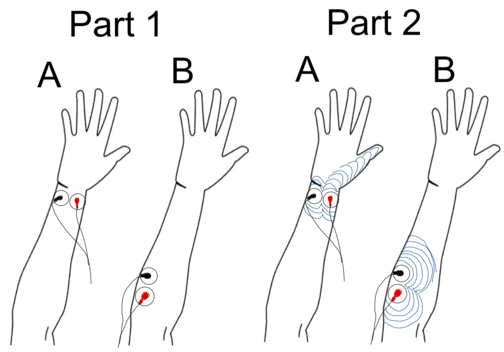

Fig. 1. Part 1: A shows the wrist placement for the control trials and the Pulse width modulation trials. B shows the forearm placement for the location comparison trials. Part 2: A shows the perceived sensation for the wrist trials, for both the current and pulse width modulation. B shows the perceived sensation for the forearm current modulation trials.

Sr. No.	Output Characteristic	Device Output 510 Ω resistor
1	Number of Output Channels: -Synchronous, alternating -Method of channel isolation	1
2	Waveform	Balanced biphasic symmetrical
3	Pulse shape	Rectangular
4	Current/voltage regulated?	Current-regulated
5	Maximum output voltage	1.5 V (3 V peak-to-peak)
6	Maximum output current	3 mA
8	Pulse duration	455.2 µs
9	Frequency	350 Hz
11	Are charge balancing cycles always completed?	Yes
23	Current Path Option (bipolar, unipolar, multipolar)	Bipolar

TABLE I

SUMMARY OF THE STIMULATION PARAMETERS USED IN THE STUDY AND THE RESULTING OUTPUT. THE OUTPUTS WERE RECORDED USING THE OSCILLOSCOPE. ALL MEASUREMENTS WERE TAKEN OVER ACROSS A 510 OHM RESISTOR.

C. Stimulation Parameters

The stimulation parameters used in the study were pulse width, current, and frequency. These were set using a Matlab program and measured using an oscilloscope. The pulse width was in milliseconds, the current in milliamps and the frequency in hertz.The resulting waveforms were balanced, symmetrical and biphasic. The output characteristic and resulting device output for all parameters can be seen in table 1.

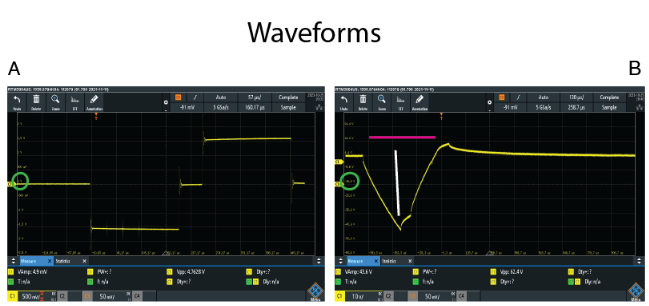

Fig. 2. A: Example waveform across 510-ohm resistor. The green circle highlights the waveform starting at 0V. B. the same waveform applied across the skin. The green circle highlights the voltage now being -15.6, rather than 0. the pink line shows the wavelength and the white line shows the amplitude of the wave. The estimated time constant is 300ms

D. Equivalent Circuit

The equivalent circuit of the electrode-tissue interface consists of a voltage source in series with a resistance-capacitance network. The voltage source represents the potential difference between the electrode and tissue. The resistance represents the resistance of the electrode-tissue interface. The capacitance represents the double layer charge at the interface. [6]

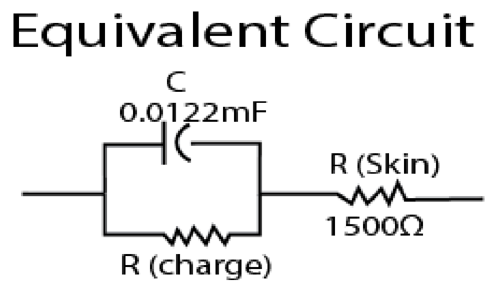

Fig. 3. Electrode-tissue equivalent circuit. C is the capacitance, found by the equation 1 / 2(pi)fR*tanP. R(charge) is the charge transfer resistance. R(skin) is the tissue/electrode resistance, found with the equation R = voltage / Current, where the voltage was found using the oscilloscope and the current was user-defined in the Matlab program

E. Experimental Design

The stimulation was delivered using the stim box and Matlab. The values for the current, pulse width and frequency were set in Matlab and sent to the stim box, which then sent the requested stimulation through the electrodes. The stimulation was delivered for 10-20seconds, the participant then had 1-5seconds to respond with their perceived magnitude score. We did initial trials in the wrist location with a constant pulse width of 200ms and frequency of 30Hz to get each participants perception threshold. These trials consisted of 7 initial readings, increasing the current by 0.2 mA steps, then using the minimum perceived value, we generated random values surrounding it to narrow down the threshold and tested each of those 7 values for 3 trials (21 total recordings). We then repeated the same trial as the perception threshold (7 readings, stepping up in value between each) for the pulse width modulation.

F. Experimental Conditions

We varied the electrode location and the pulse width. For the control, we used the perception threshold found at the wrist. We then completed the same trials at the forearm to get the forearm perception threshold. The pulse width modulation was done at the wrist location. The values varied for each participant, given the variation in each persons' ability to perceive sensation. The table below shows the perception thresholds for each participant at each location.

Participant Perception Thresholds

	1	2	3	4
Wrist	2.375	1.75	2.15	1.55
Forearm	1.64	1.186	1.575	1.1475

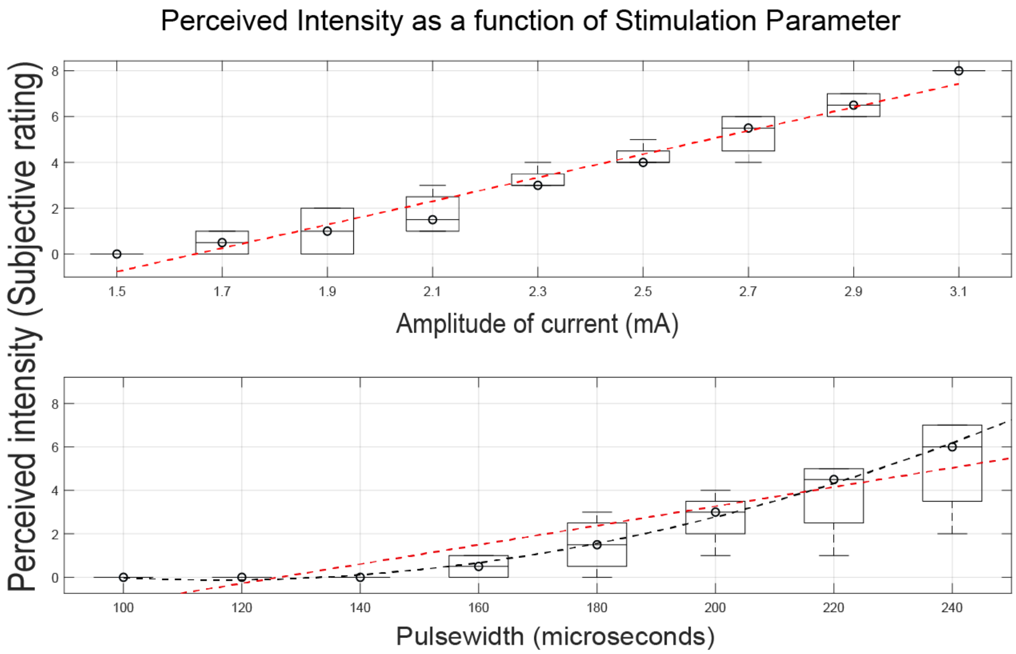

Fig. 4. Box plots of the perceived intensity as a function of the stimulation parameter. The top plot shows the plots for the amplitude of the current with the line of best fit. The slope of the line is 1.025. The bottom plot shows the plots for the pulse width with two lines of best fit. the linear lines slope is 0.8869 and the curved line is 0.1637.

G. Line of Best Fit

The line of best fit for figure four was found using the Matlab polyfit function, which returns the slope and y-intercept. For the pulse width graph, the linear line did not seem to be the best fit, so a quadratic line was also added, which seems to represent the data better (figure 4). For figure 5, the average values for the pule width and forearm trials for each participant were found. A line of best fit was then calculated for each participant, using linear regression. The slopes of these lines were averaged and plotted (figure 5).

H. Statistical analysis

Deviations from normality were checked using the Anderson-Darling test and histograms (n = 28). The data was found to be not normally distributed. Then, a paired Wilcoxon signed rank test was used to test the hypothesis that there is a significant difference between perceived sensation for each parameter (n = 8). We then applied the standard error of the mean for each parameter (n = 2).

III. Results

A. There was a difference in the programmed and measured values for stimulation

The stimulation was performed using a stimulation box (stim box) and 3.6cm diameter, medi trace electrodes. The electrodes were first placed on the ventral wrist crease and the current and pulse width modulated using Matlab. Then, the electrodes were placed on the medial cutaneous nerve of the forearm and the current modulated using Matlab. The parameters readings were verified using the oscilloscope to compare the values to what was programmed. When 2.5mA was set as the current in the program, 4.9mV was seen across the 510ohm resistor and 4.3mV was seen across the skin (figure 2). There was also a difference in the pulse width. It was set to 800ms in the program, but as seen in table 1, the pulse duration was 455.2ms.

B. The equivalent circuit for the electrode-tissue interface had a resistance of 1500 ohms

The equivalent circuit of the electrode-tissue interface consists of a voltage source in series with a resistance-capacitance network. The electrode-skin resistance decreases with frequency. At lower frequency, the resistance is much lower than at higher frequency. On the other hand, the capacitance increases with frequency, so a higher frequency is preferred. We chose a balance between the two to get the optimal circuit. We calculated the resistance by doing the voltage divided by the current. The capacitance was calculated using the equation 1 / 2(pi)fR*tanP. The value for resistance was found to be 1500 oms, and capacitance as 0.0122. The design of the circuit and the values can be seen in figure 3.

C. The location of the electrodes has a significant impact on the perception threshold

We varied the pulse width and the location of the electrodes to see which had a significant impact on the perception threshold. We modulated the pulse width from 100-240ms and the location from the wrist to the forearm. At the forearm location, we varied the current around the minimum perceived for each participant to understand the minimum amount of stimulation that would cause sensation. For the forearm current trials, the

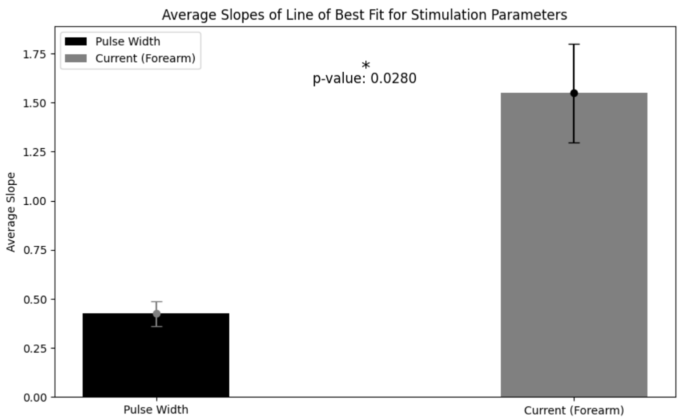

Fig. 5. Comparison between the average slopes for the data of each participant. The p-value of 0.0280 was found using a paired wilcoxon signed rank test. The significance level used was p = 0.05. There is a significant difference between the perceived magnitude of sensation for the pulse width modulation and the electrode location parameters.

slope of the line of best fit was found to be 1.025, which for the wrist pulse width trials the slope of the line of best fit (curved line seen in bottom plot of figure 4) was 0.1637. These slopes show that the rate of change (or perception) for the pulse width is much slower and overall not as high as with the other parameter (location). A direct comparison between these slopes shows a significant difference (p = 0.0280) between the effect of the pulse width and location (figure 5).

D. The preferred sensation comes from a combination of current modulation and optimal location

Overall, the effect of location on the perceived sensation was much higher for all participants and a preferred feeling over the pulse width modulation. One participant found adjusting the pulse width to be more uncomfortable, without increasing the overall magnitude of the sensation. Another participant stated that their ”thumb could go numb” when the pulse width was increased, while the feeling at the forearm gets ”more intense and stronger, but not painful”.

IV. Discussion

The objective of this study was to identify the optimal parameter selection to illicit sensation, while keeping stimulation low. We found that the location has a significant impact on the perception threshold as compared to the wrist, and overall lowers the necessary stimulation to create sensation. We also found that changing the pulse width has a minimal impact on the perception threshold and can cause discomfort faster than current modulation.

Prior work has shown the impact that electrode placement can have on sensation [7]. Prior work has also shown how pain thresholds can cause significant variations in perception thresholds for electrocutaneous stimulation [8]. In contrast, we used a baseline for each participant to determine the perception threshold, not a universal stimulus. We also used only one channel of stimulus, rather than two, to look at the effect of location on sensation.

The work presented here builds off of prior works by running with the findings that location effects perception threshold and that different people can have different thresholds, but builds off of this idea by comparing other stimulation parameters to location to see what has a more significant impact and which is preferred by participants. Also novel from this work, we used only single channel stimulation, which increases the difficulty of creating sensation at lower stimulus values. We followed very similar methods to Geng et al. but instead looked at lower stimulus and the impact on the minimum perception threshold.

Future work should continue to narrow down what the optimal electrode location is to create sensation with minimum stimulation, both in the current and pulse width. The study should also be replicated with more participants, specifically of a different gender and wider age gap.

This work provides a starting point for more optimal electrode location and stimulation parameter selection that can be used to increase haptic feedback for prosthetics and lower the current cognitive, visual load that is needed to operate them effectively. This will also help to decrease prosthetic rejections due to the inability to operate them [9] These findings can also be applied to virtual reality, such as haptic rendering for equine therapy for veterans.

V. Author Contribution

RM wrote the manuscript and performed statistical tests. CA helped design the study. GO recorded the findings and recordings. NP modulated the values and set up the hardware.

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