Stimulation Parameters Effects on Perceived Magnitude

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***Abstract*—The long-term goal of this research is to explore the effects of various stimulation parameters on perceived magnitude of the sense. The number of Americans with limb loss is 1 in 190 and expected to double by 2050. Electrical properties of neurons and the basic nerves that communicate sensory information are still present in the residual limb of amputee individuals and can be utilized to restore sensory feedback. Prior work has covered the effects of various stimulation parameters, but has not explore pulse amplitude. Results showed that collective remarks agreed that pulse-amplitude provided improved sensory discrimination compared to pulse-width. Within the results, a charge-balanced stimulation was safely delivered to participants and an RC circuit did mimic an electrode-tissue interface. The results provide a stepping stone in neuroprostheses towards gaining more knowledge of sensory feedback. They may also be applied to adjacent fields, such as other assistive therapies for regaining sensory feedback after events such as strokes**

I. Introduction

Currently, nearly one in 190 Americans live with limb loss. This number is predicted to double by the year 2050 [1]. As the number of individuals with this neurological impairment is likely to grow, it is important that efforts are focused on creating more intuitive tools to help these individuals adjust and improve their quality of life. Current clinical standards of care for these individuals focus on addressing pain treatment, exercise therapy, and educating these patients and their caregivers [2]. Although those aspects are vital, there are limitations when it comes to activities of daily life or leisure activities, and community integration [2]. One vital component to improving traditional prostheses is the incorporation of effective sensory feedback.

Due to the electric spike behavior between the human brain and the body's senses, engineers can take advantage of the electrical communication from the senses to the brain to artificially deliver different sensations to the individuals through electrical stimulation. When a limb is lost, becomes paralyzed, or less functional, the majority of the nerve wiring are still intact and functional [3]. Utilizing these frameworks to deliver sensory information can lead to a variety of helpful applications for individuals of all different neurological impairments.

Previous state-of-the-art research on sensory feedback consists of exploring different ways to electrically stimulate healthy participants and obtain their feedback on the perceived magnitude of the stimulation. Graczyk et al have conducted such an experiment and explored the stimulation parameters of pulse frequency and pulse width. The research found a quantitative way to map the correlations between the stimulation variances and the perceived magnitude [4].

The objective of this paper is to expand upon the work of Graczyk et al by further exploring another stimulation parameter – the current amplitude. As this is parameter had not been explored by Graczyk et al, it will provide more useful insight and more information about sensory feedback and its relation to perceived magnitude. The findings from this paper conclude that a charge-balanced biphasic stimulation can be successfully and safely delivered to the index finger. In addition, an RC circuit with a resistance of 1.46 kΩ and a capacitance of 22.7 nF can effectively mimic the effects of an electrode-tissue interface. Although no statistical significance was found between the perceived magnitude slopes of each participant, positive overall subjective remarks were received that collectively agree that pulse-amplitude provides improved sensory discrimination when compared to pulse-width.

II. Methods

The following section reviews the specifications of this study outlined through a variety of subsections, including participants, stimulation hardware, stimulation parameters, etc.

A. Participants

The research data acquired within this paper was collected through experiments with three participants. The group was 100% female and their ages ranged from 21-22 years-old. All participants were considered healthy in terms of neurological condition.

B. Stimulation Hardware

The two primary hardware components that were used in this study were the stimulation box and the surface electrodes that connected the box to the subjects. The electrodes were 3cm in diameter and were placed on the top and bottom of the index finger on the right hand, as shown in Fig. 1a. The stimulation box was a one-channel high-voltage stimulator developed in the University of Utah's NeuroRobotics lab. Its compliance voltage within this experiment was 1 volt.

C. Stimulation Parameters

The two stimulation parameters used for independent exploration in this study were the stimulation waveform's pulse

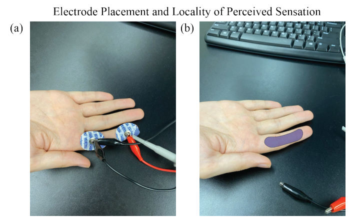


Fig. 1. (a) Image of electrode placement on the index finger of the right hand. (b) Annotated image of the perceptive field where sensation was felt by participants.

width and current amplitude. Generally, the pulse width was measured by looking at the time that elapsed during the anodic or cathodic phase. Either phase can be used in this case since we are utilizing a charge-balanced biphasic waveform. The current amplitude was measured by observing the peak-to-peak voltage within the waveform and following Ohm's law to obtain the current. Table 1 includes all of the output characteristics for the generated stimulation waveform. In practice, both stimulation parameters were updated manually through a MATLAB script that generated commands to the stimulation box.

D. Time Constant Calculation

An equivalent circuit was structured to mimic the electrode-tissue interface. The circuit was created using an RC circuit to capture the faradaic and non-faradaic reactions [5]. Since the waveform is current regulated, a current source was placed in the circuit, as seen in Fig. 3. The resistance and capacitance values were obtained using node-voltage circuit analysis and plugging in the appropriate voltages to the capacitance and resistance equations. Ultimately, the capacitance was 22.7 nF and the resistance was 1.46 kΩ. The time constant was calculated by taking the actual waveform characteristics, denoted in Fig. 2b with labels (2), (4), and (5). The time constant value came out to 33.3 μsec.

E. Experimental design and metrics

For each participant, each stimulation parameter had a series of six trials per round, therefore, six values for the stimulation parameter were tested on each round. The participants were asked to rate their perceived magnitude on a scale of 1-10, where 1 is the weakest and 10 is the strongest. The individual simulations lasted for 1 second each and the participant had 3 seconds to give a rating between simulations. There were a total or three rounds to ensure results over multiple samples. The parameter values were stimulated in increasing order during the first round so the participant can obtain a general sense of the scale. The following two rounds continued to test the same six trial parameter values, but the order of stimulation was randomized to avoid recognition of patterns.

Table 1

Output Characteristics	Device Output
Number of Output Channels (Synchronous or alternating, Method of channel isolation)	1
Waveform (e.g., charge balanced biphasic symmetrical, biphasic asymmetrical)	Charge-balanced biphasic symmetrical
Pulse Shape (e.g., rectangular, sinusoidal)	Rectangular
Current/voltage regulated? Compliance voltage (if current source)?	Current Regulated. Compliance Voltage = 1V
Maximum Output Voltage (specify units) (+/-__%)	1V (+/- 0.07V)
Maximum Output Current (specify units) (+/-__%)	1.8mA (+/- 0.03mA)
For multiphasic waveforms (Symmetrical or Asymmetrical phases?, Phase Duration (include units) (state range, if applicable) (both phases, if asymmetrical)	symmetrical phase, 200-275 us
Pulse Duration (specify units)	Parameter 1: 500us. Parameter 2: 200us
Frequency (Hz)	30 Hz. Parameter 1: 29.97 Hz. Parameter 2: 29.968 Hz
Method of Balancing Charge	Actively
Are charge balancing cycles always completed?	Yes
Net Charge (µC per pulse) @ 500Ω	0uc(charge balanced)
Leakage Current8 (nA) @ 500Ω	0nA (charge balanced)
Net DC Current9 (µA) at maximum pulse rate @ 500Ω	0ua (charge balanced)
Maximum Phase Charge (µC) @ 500Ω	0.0000006666666667
Maximum Charge Density10 (µC/cm²/phase) @ 500Ω	0.000000094314086
Maximum Phase Power (W/phase) @ 500Ω	0.002244901961
Maximum Phase Power Density (W/cm²/phase) @ 500Ω	0.0003175888171
Pulse Delivery Mode (continuous/bursts (pulse trains))	continuous pulse train
Burst Delivery: a. Pulses per burst; b. Bursts per second; c. Burst duration (seconds); and d. Duty Cycle [Line a X Line b]	N/A
ON Time (seconds)	1 sec
OFF Time (seconds)	3 sec
Current Path Options (bipolar, unipolar, multipolar)	Bipolar
Additional Features, if applicable	N/A

The pulse-width stimulation parameter covered a range of 200μsec - 275μsec. The six discrete values tested were $[200, 215, 230, 245, 260, 275]$. The current amplitude stimulation parameter covered a range of 1.3mA - 1.8mA. The six discrete values for this parameter were $[1.3, 1.4, 1.5, 1.6, 1.7, 1.8]$.

When analyzing the perceived magnitude plots of both parameters, a best fit line was created through the boxplots, as seen in Fig. 4. The slope of the best fit lines were determined using simple linear regression between the boxplot's median values. As a result, the best fit lines for the pulse-width and amplitude parameters could be described with $y = 0.0387x - 6.0688$ and $y = 11.905x - 14.286$ respectively.

F. Statistical Analysis

To begin the statistical analysis, the data was tested to detect any outliers and remove them when necessary. Then, a test of normality was conducted on the cleaned data and the data was determined to not be normally distributed. The data was considered to be paired as multiple of the same trials were conducted again on the same participant. There was a sample size of 18 per parameter per individual.

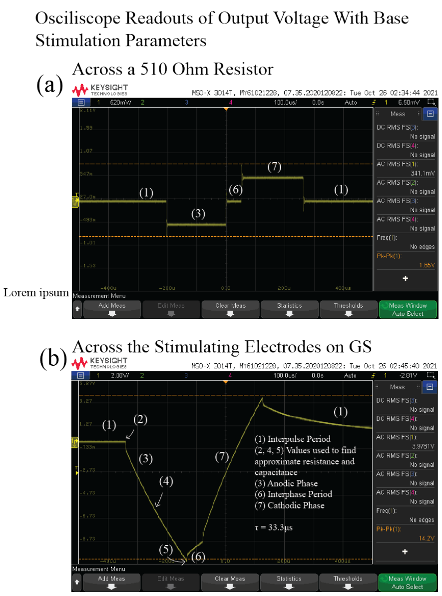


Fig. 2. (a) Example waveform across a 510-ohm resistor. (b) Example waveform when the same waveform from part a is applied across the skin. Relevant waveform components, such as the interpulse period, anodic phase, etc., are labeled in the figure. If modeled as an RC circuit, the estimated time constant of the skin would be 33.3 μsec.

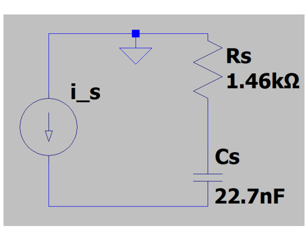


Fig. 3. Equivalent circuit describing the electrode-tissue interface.

III. Results

A. A charge-balanced biphasic stimulation was successfully delivered to the index finger.

The stimulation was performed by placing two electrodes on the top and bottom of the index finger on the right hand, as shown in Fig. 1a. The pulse-width stimulation parameter was measured by viewing how long the anodic or cathodic phase were active. The amplitude stimulation parameter was measured by obtaining the peak-to-peak voltage amplitude and dividing by the resistance, according to Ohms law. The biggest difference between the programmed and measured outputs were the waveform shapes. Although they had similar characteristics, as expected, the measured output certainly had a capacitative component introduced by the skin that the measured output did not, clearly visible in Fig. 2. More information about the stimulation waveform characteristics may be found in Table 1.

B. The RC equivalent circuit had a resistance of 1.46 kΩ and a capacitance of 22.7 nF.

The equivalent circuit was structured using an RC circuit with a current source. The resistance and capacitance values were calculated using node-voltage circuit analysis and the appropriate capacitance and resistance equations. As seen in Fig. 3, the capacitance and resistance values were 22.7 nF 1.46 kΩ, respectively. The time constant was evaluated to be 33.3 μsec.

C. No statistical significance was found between the slopes of each participant.

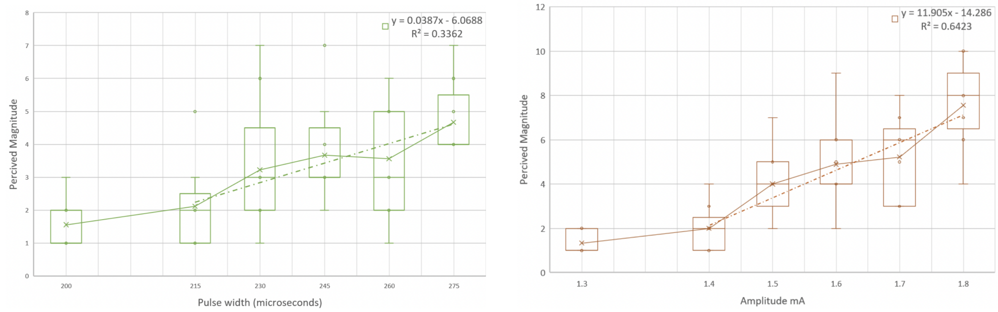
The two stimulation parameters that were varied were the pulse-width and the current amplitude. The pulse-width range took on the following values: $[200, 215, 230, 245, 260, 275]$. The current amplitude range covered the following values: $[1.3, 1.4, 1.5, 1.6, 1.7, 1.8]$. When analyzing perceived magnitude plots in Fig. 4, the best fit lines for the pulse-width and amplitude parameters could be described with $y = 0.0387x - 6.0688$ and $y = 11.905x - 14.286$, respectively. Based on individual slope analysis, as seen in Fig. 5, there was no statistical significance between any of the individuals.

D. Positive overall subjective remarks were received.

A disclaimer should be stated that remarks mentioned are subjective, but can still be useful information for the improvement of future experiments. With this in mind, generally positive feedback was received about the experiments. Collectively, participants agreed that it was much easier to discriminate sensations using the amplitude parameter than it was using the pulse-width parameter. Some of the pulse-width parameter values seemed indistinguishable to most of the participants.

IV. Discussion

This paper's objective was to expand upon the work of Graczyk et al by further exploring the current amplitude as a new stimulation parameter. The findings from this paper



a. Pulse Width Stimulation Parameter

b. Amplitude Stimulation Parameter

Fig. 4. Perceived Magnitude plots as a function of stimulation parameters. A best fit line is plotted alongside the boxplots.

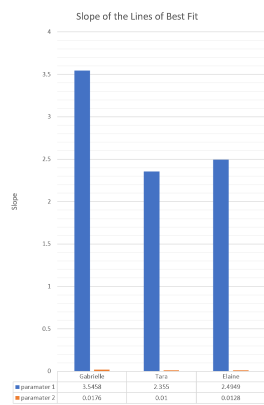


Fig. 5. Barplot of the slopes of the lines of the best fit for each participant and each stimulation parameter. None of the data sets were statistically different from each other.

concluded that a charge-balanced biphasic stimulation can be successfully and safely delivered to the index finger. In addition, an RC circuit, with a resistance of 1.46 kΩ and a capacitance of 22.7 nF, can effectively mimic the effects of an electrode-tissue interface. Although no statistical significance was found between the perceived magnitude slopes of each participant, collective remarks agreed that pulse-amplitude provided improved sensory discrimination when compared to pulse-width.

Prior work has shown that there is in fact a direct relationship between certain stimulation parameters, such as pulse-width and pulse-frequency, and perceived magnitude. Prior work has also shown that these factors can be characterized by a single computational term to help predict perceived magnitude [4]. In contrast, here we show that there are other parameters, specifically the pulse-amplitude, that may also have an impact on perceived magnitude and may be stronger than those considered in the prior work.

The work presented here builds off of prior work by exploring a parameter that had not yet been explored by Graczyk et al, which provides more useful insight and more information about sensory feedback and its relation to perceived magnitude. Also novel from this work is its method for statistically analyzing its results using a comparison between perceived magnitude plot slopes.

Future work should replicate these findings with additional participants to ensure that the statistical analysis of no statistical difference is accurate. In addition, future work should expand the range of values for the pulse-width in an effort to improve the perceived magnitude with this parameter.

This paper's work has a direct impact on the field of neuroprostheses by contributing more knowledge of sensory feedback for perceived magnitude. The findings may also be applied to adjacent fields, such as the development of other assistive devices in therapies for regaining sensory feedback after events such as strokes. Clinically speaking, the development of this work provides a foundation for improvements in prostheses and their grasping sensitivity. Improvements in prostheses can significantly impact the quality of life for amputees, providing a better approach for daily tasks and independence.

V. Author Contributions

All authors contributed to the experiment design and parameter decisions. PTZ, EW, and GS were involved in participant data collection, parameter range selection, and characterizing output waveforms in Table 1. GS conducted the RC circuit analysis. EW and HK performed statistical analysis.

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