Percieved Intensity Increases with Increased Frequency and Pulse Width in Transcutaneous Electrical Nerve Stimulation

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The long-term goal of this research is to gain a greater understanding of how altering of transcutaneous electrical stimulation parameters affects the strength and modality of the perceived stimulus. Roughly 400,000 people in the U.S. have upper limb amputations, a large proportion of which have abandoned their prostheses in part due to functional limitations by limited sensory feedback. Recent research has demonstrated success integrating transcutaneous electrical stimulation into prostheses to enable the wearer to detect object properties such as stiffness with the prosthetic hand. We sought to further understand how stimulation parameters alter perceived stimulus intensity, and found that perceived intensity increased with increasing pulse width and frequency. Both showed positive slopes when perceived intensity (normalized) was plotted against both frequency and pulse width (medians (0.0065 and 0.0012 respectively). These results may lead to better prosthetic control through tactile feedback. These results could additionally yield improvements in the accuracy of virtual reaity and telepresence through tactile feeback.

I. Introduction

Approximately 400,00 people in the U.S. are upper limb amputees [1]. Myoelectric and body-powered prostheses are rising to prominence as they allow some motor function of the prosthetic limb, however, they still have high abandonment rates of approximately 39% and 50%, respectively [2], and one of the reasons they are frequently abandoned is that the functionality of the prostheses for activities of daily living is limited by a lack of sensory feedback [3].

Direct interaction with the skin's surface can result in the activation of afferent somatosensory fibers which relay pressure, vibration, temperature, and pain information to the brain [4]. However, in the absence of a skin surface, such as on a prosthesis, afferent fibers in the residual limb can be stimulated artificially and non-invasively through transcutaneous electrical nerve stimulation (TENS) to provide artificial somatosensations [5].

TENS has been used in recent research and development stage prosthetics to provide haptic feedback, and has been shown to enable stiffness detection of grasped objects [6] and determination of object shape and surface topology [7].

The objective of this paper is to investigate how modulating different parameters of TENS delivery affects the perceived intensity and modality of haptic feedback. Uniquely, our study addresses the wide range of individual differences in reported perceived somatosensation given the same stimulation parameters. We found that stimulation ran across resistor shows markedly lower recorded voltages, our equivalent circuit model of electrode tissue interface shows a resistance of 74.4 kiloohms and capacitance of 537.6 pF, perceived Intensity increases with both increasing frequency and increasing pulse width, and reported Sensations from Similar TENS are Highly variable between individuals**.**

II. Methods

A. Participants

Our participant pool was comprised of four neurologically healthy participants, ages ranging from 21 to 24, with a gender make-up of 25% male, 75% female. One participants data (23 year old female) is only present for analysis of the frequency parameter data due to inability to attend pulse width parameter data collection sessions.

B. Stimulation Hardware

A one channel high-voltage stimulator was used to provide transcutaneous electrical nerve stimulation. The compliance voltage was unable to be measured by the oscilloscope. Stimulation was transmitted to the body via two Cardinal Health Kendall ECG H124SG electrodes placed approximately 2 cm apart from each other on the medial forearm. The conductive hydrogel area of the electrodes had a surface area of 201 mm.

C. Stimulation Parameters

The high-voltage stimulator had a single output channel which delivered charge-balanced, biphasic, asymmetrical waveforms. The pulse shapes were sinusoidal and we utilized a maximum output current of 1.5 mA. For experiments not testing effects of pulse duration we kept pulse duration at 200 µs, and for experiments not testing the effects of frequency we kept frequency at 30 Hz. When testing the effects of pulse duration we used pulse durations in a range of 100 - 1000 us. When testing the effects of frequency we used frequencies in a range of 10-100 Hz. The stimulator balanced charges by delivering pulse phases of equal and opposite charge, however charge balancing cycles were not always completed. The net charge reading on the oscillator after applying charge across a 500 Ohm resistor was 0. Oscillator measurements when the 500 Ohm resistor was used were mostly not able to be read, however, the maximum phase power with the 500 Ohm resistor was determined to be 0.00175 W. Pulses were delivered continuously rather than in bursts and the current had a biopolar path.

Output Characteristic	Device Output
Number of Output Channels	1
Waveform	Charge balanced biphasic asymmetrical
Pulse Shape	Sinusoidal
Current/Voltage Regulated? Compliance Voltage?	NA
Maximum Output Voltage	NA
Maximum Output Current	1.5 mA
For Multiphasic Waveforms: • Symmetrical or asymmetrical phases? • Phase Duration	• Asymmetrical phases • 200µs
Pulse Duration	100-1000 µs (increments of 100)
Frequency	10-100 Hz (increments of 10)
Method of Balancing Charge	Delivering pulse phases of equal and opposite charge
Are charge balancing cycles always completed?	No
Net Charge @ 500 Ω	0
Leakage Current @ 500 Ω	NA
Net DC Current at maximum pulse rate @ 500 Ω	NA
Maximum Phase Charge @ 500 Ω	NA
Maximum Charge Density @ 500 Ω	NA
Maximum Phase Power @ 500 Ω	0.00175W
Maximum Phase Power Density @ 500 Ω	NA
Pulse Delivery Mode	Continuous
Burst Delivery: a. Pulse per burst b. Bursts per second c. Burst duration (seconds) d. Duty cycle	NA
ON Time (seconds)	NA
OFF Time (seconds)	NA
Current Path Options	Bipolar
Additional Features, is applicable	NA

D. Time Constant Calculation

Capacitance and resistance were calculated through oscilloscope readings and the equation below.

Where $\tau = 40\ us, R_c = \frac{\Delta V_c}{0.07*1mA} = 74.4\ k\Omega\ , C = \frac{\tau}{R_c} = 537.6\ pF$

E. Experimental Design and Metrics

For testing perception of stimulation at various frequencies, participants were given 10 different stimulations, all at the same amplitude and pulse width but at 10 different frequencies. The stimulations were delivered in a different random order for each participant, with each different frequency being presented only once per participant. Participants were blinded to the parameters of stimulation. Participants were given as much time as they needed to provide information on whether or not they could feel individual pulses, subjective ratings on a scale of 1-10, 1 being least intense and 10 being most intense, of perceived buzzing and perceived pressure, and to provide other con the quality and location of the sensation. Perceived intensity was determined by averaging buzzing and pressure scores. For testing perception of stimulation at various frequencies, participants were given 10 different stimulations, all at the same amplitude and frequency but at 10 different pulse widths. The stimulations were delivered and feedback was collected in the same manner as for frequency tests, except participants were asked to give 1-10 ratings on perceived "sharpness" rather than perceived buzzing, and perceived intensity was determined by averaging sharpness and pressure scores.

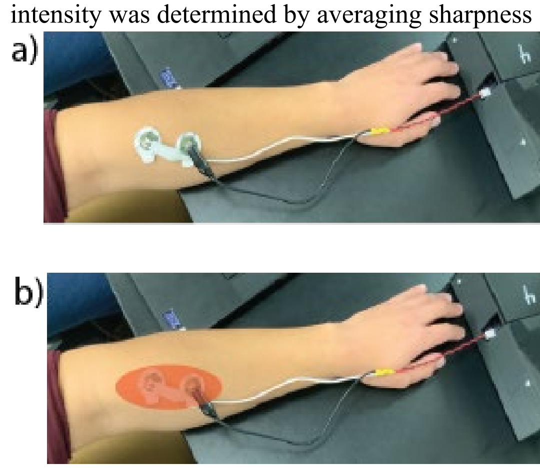

Figure 1 a) electrode placement b) area where sensation was felt

Frequency was the first varied stimulation parameter. Amplitude of stimulation was kept at 1.5 V and pulse width at 200 us. We tested perceived stimulus intensity and obtained participant feedback at frequencies of 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 Hz. Pulse width was the second varied stimulation parameter. Amplitude of stimulation was kept at 1.5 V and frequency at 30 Hz . We tested perceived stimulus intensity and obtained participant feedback at pulse widths of 100, 200, 300, 400, 500, 600, 700, 800, 900 and 1000 us.

Slopes for perceived intensity vs. frequency, and perceived intensity vs pulse width were determined for each participant by using the values of perceived intensity for each parameter variation as “points” to which a line was fitted in MATLAB using the polyval function, and slope was calculated from the resulting best fit line created by polyval by dividing the range in y (perceived intensity) values over x (frequency or pulse width) values.

F. Statistical Analyses

For plotting perceived intensity values for each parameter, as well as comparing slopes of perceived intensity for frequency against perceived intensity for pulse width, histograms and Anderson-Darling tests were performed to assess normality (N=4 for perceived intensity for frequency plots, N = 3 for perceived intensity for pulse width plots, N = 3 for comparison of slopes). All data was non-parametric except for perceived values for 10 and 100 Hz in frequency. Therefore an Wilcoxon Signed Rank Test was used to compare and test statistical significance for paired slope data, which necessitated omitting data from one participant. Corrections for multiple comparisons were not necessary.-

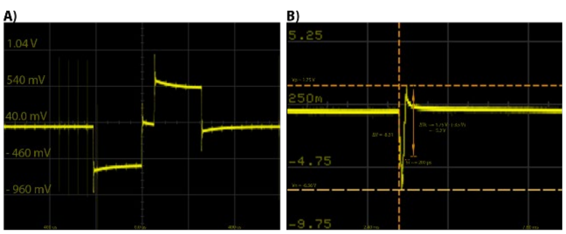

Figure 2 pulse as seen on oscilloscope with skin (a) and 500 Ohm resistor (b)

III. Results

A. Stimulation ran across resister shows markedly lower recorded voltages.

Stimulation was performed with a one channel high-voltage stimulator using 1.5 V and varying pulse widths and frequencies. 2 electrodes for stimulation were placed on the medial forearm (Fig 1). We measured stimulation parameters via an oscilloscope both with the stimulator connected to skin and the stimulator connected to a 500 Ohm resistor. Across the resistor the measured voltage dropped dramatically (Fig 2).

B. Equivalent circuit model of electrode tissue interface show a resistance of 74.4 kiloohms and capacitance of 537.6 pF

Our model for our definition of the equivalent circuit for the electrode tissue interface is seen in (Fig 3). We used the following equations to calculate the resistance and capacitance

$$\text{Where } \tau = 40\ us, R_c = \frac{\Delta V_c}{0.07 * 1mA} = 74.4\ k\Omega\ , C = \frac{\tau}{R_c} = 537.6$$

values of the circuit, and from the equation obtained a resistance of 74.4 kiloohms and a capacitance of 537.6 pF

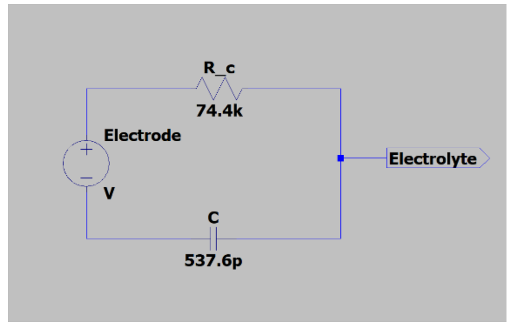

Figure 3 equivalent circuit model

C. Perceived Intensity increases with both increasing frequency and increasing pulse width.

One paragraph including: 1) a brief recap of the different stimulation parameters you varied and how they are defined, 2) a summary of what the slopes were with statistics, 3) a reference to Fig. 4 and Fig. 5

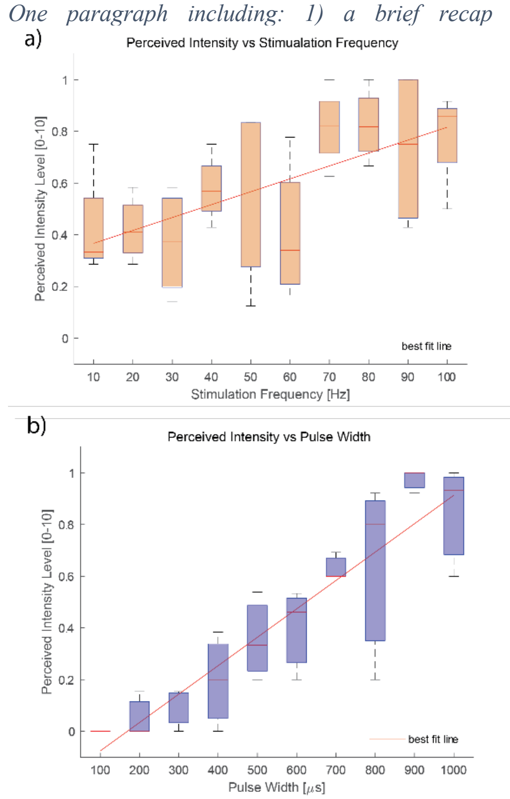

Figure 4. Perceived intensity as a function of stimulation frequency (a) and pulse width (b)

In this section we measured perceived intensity on a scale of 1-10 in response to changing frequency and pulse width (Fig 4) (10 being most intense, normalized by each participants highest value), and calculated the slope of perceived intensity/change in parameter, which we compared (Fig 5). There were no significant differences between slopes for frequency (median 0.0065) and pulse width (median 0.0012 ($p = 0.25$ on Wilcoxon Signed Rank, N = 3)

D. Reported Sensations from Similar TENS are Highly Variable Between Individuals.

Most notably of the subjective feedback we received from participants, is that the sensations varied greatly from individual to individual. So much so that each subject's individual data had to be normalized to the highest reported perceived intensity value from each participant because some participants felt the stimuli very strongly and had most perceived intensity values above 6, while others only felt mild sensations from the same parameter stimulations and hardly reported percieved intensity values over 3. Additionally, at low frequencies each participant had a different frequency threshold at which they were no longer able to discriminate individual pulses. Additionally, some noted that high frequency stimuli had a pleasant valence, while others found the stimuli noxious.

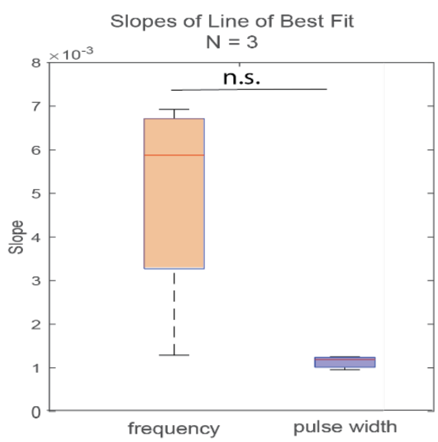

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Figure 5 Line of Best Fit slopes: no significant difference between frequency and pulse width on Wilcoxon signed rank (median 0.0065 and 0.0012, p = 0.25)

IV. Discussion

The objective of this paper was to investigate how modulating different parameters of transcutaneous electrical stimulation delivery affects perceived intensity and modality of haptic feedback. We found that stimulation ran across resistor shows markedly lower recorded voltages, our equivalent circuit model of electrode tissue interface shows a resistance of 74.4 kiloohms and capacitance of 537.6 pF, perceived Intensity increases with both increasing frequency and increasing pulse width, and reported Sensations from Similar TENS are Highly variable between individuals.

Prior work by D'Anna et al. has shown that peripheral sensory fibers can be stimulated non-invasively by transcutaneous electrical nerve stimulation [5]. Previous work by Vargas et al. as also shown that this form of haptic feedback can be used in research grade prostheses to enable wearers to recognize objects by touch detect object stiffness with an artificial hand [6,7]. In contrast, here we show intensity of stimulation can be modulated by increasing or decreasing frequency and pulse width.

The work presented here builds off of prior works by D'Anna et al. demonstrating the ability of transcutaneous electrical stimulation to elicit artificially evoked somatosensation. Novel from this work is elucidation of how frequency and pulse width can be altered to modulate intensity and modality of somatosensation.

Future work should replicate these findings with additional participants and with a wider range of tested frequencies and pulse widths to obtain more variation in percieved intensity within each individuals responses. Additionally future work should refine operational definitions of and measurement of perceived intensities and modalities to provide more accuracy and standardization to subjective participant responses.

The immediate impact to the field is a greater understanding of how parameters of transcutaneous electrical be stimulation may modulated to in turn modulate intensity and modality of haptic feedback from neuroprostheses. The information gained from this study may help yield innovations in haptic feedback use for more realistic virtual reality technology and telepresence. Lastly this work may provide a foundation for more functional, haptically guided, prosthetic control which could ultimately result in improved dexterity lower prosthesis rejection rates among amputees.

Author Contributions

DL, KH, JLR, and ES were responsible for the design and execution of frequency experiments. KH, JLR, and ES were responsible for design and execution of pulse width experiments. JLR was responsible for calculating the equivalent circuit and generating and editing figures 2 and 3. KH and ES were responsible for data analysis, and generating table 1, figure 4 and figure 5. DL was responsible for generating figure 1 and editing figures 4 and 5. All parties wrote their own conference proceeding.

References

[1] M. P. Fahrenkopf, N. S. Adams, J. P. Kelpin, and V. H. Do, "Hand Amputations.," *Eplasty*, vol. 18, p. ic21, 2018.

[2] E. Biddiss, D. Beaton, and T. Chau, "Consumer design priorities for upper limb prosthetics," *Disability and Rehabilitation: Assistive Technology*, vol. 2, no. 6, pp. 346–357, Jan. 2007, doi: 10.1080/17483100701714733.

[3] S. L. Carey, D. J. Lura, M. J. Highsmith, CP, and FAAOP, "Differences in myoelectric and body-powered upper-limb prostheses: Systematic literature review," *J Rehabil Res Dev*, vol. 52, no. 3, pp. 247–262, 2015, doi: 10.1682/JRRD.2014.08.0192.

[4] H. P. Saal and S. J. Bensmaia, "Touch is a team effort: interplay of submodalities in cutaneous sensibility," *Trends in Neurosciences*, vol. 37, no. 12, pp. 689–697, Dec. 2014, doi: 10.1016/j.tins.2014.08.012.

[5] E. D'Anna *et al.*, "A somatotopic bidirectional hand prosthesis with transcutaneous electrical nerve stimulation based sensory feedback," *Sci Rep*, vol. 7, no. 1, Art. no. 1, Sep. 2017, doi: 10.1038/s41598-017-11306-w.

[6] L. Vargas, H. Huang, Y. Zhu, and X. Hu, "Stiffness Perception using Transcutaneous Electrical Stimulation during Active and Passive Prosthetic Control," in *2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC)*, Jul. 2020, pp. 3909–3912. doi: 10.1109/EMBC44109.2020.9176078.

[7] L. Vargas, H. Huang, Y. Zhu, and X. Hu, "Object Shape and Surface Topology Recognition Using Tactile Feedback Evoked through Transcutaneous Nerve Stimulation," *IEEE Transactions on Haptics*, vol. 13, no. 1, pp. 152–158, Jan. 2020, doi: 10.1109/TOH.2020.2967366.