Merged Haptic Sensation in the Hand during Concurrent Non-Invasive Proximal Nerve Stimulation

Luis Vargas, He (Helen) Huang, Yong Zhu, and Xiaogang Hu

Abstract— **When individuals interact with the environment, sensory feedback is a critical aspect of the experience. Individuals using prosthesis often have difficulty controlling their device, partly due to a lack of sensory information. Transcutaneous nerve stimulation has the potential to elicit focal haptic sensation when controlled electrical current was delivered to a pair of electrodes in proximity to the nerve. The objective of this preliminary study was to evaluate how different elicited focal haptic sensation were altered, when multiple concurrent electrical stimuli were delivered to different portions of the median and ulnar nerve bundles. The delay between the individual stimulation during concurrent stimuli was also varied to identify if this parameter could alter the resulting sensation region. Lastly, the stability/repeatability of the perceived sensation during concurrent stimuli was determined. Our preliminary results showed that the spatial distribution of the haptic sensation was largely a direct summation/merge of the sensation regions from the individual nerve stimulation when comparing the regions to that of the concurrent double stimulation. Our results also showed that merged sensation region was not sensitive to different time delays the two concurrent stimuli. Lastly, the sensation regions remained stable and showed repeatable sensation in the hand even with 20-60 minutes between repeated stimulations.**

I. Introduction

Haptic perception allows individuals to interact with the world around them while limiting the need to rely on other sources of information. The ability to use feedback received from the nerves located on the human hand is an important human advantage. Upper arm amputations take away this essential source of sensory information while at the same time resulting in a loss of motor function [1]. Prosthetic devices in recent years have shown major improvements in the ability to replicate some of the motions seen in the hand during daily activities. However, many of these devices are restricted since sensory feedback is not incorporated [2]. Various modalities have been tested to restore/reduce the sensory deficits. Many of these methods result in non-somatotopically matched or somatotopically matched (with a phantom limb) sensation that is caused by either mechanical/electrical tactile inputs [3-6] which activate sensory receptors or by stimulating sensory nerves directly.

Non-somatotopically matched sensation can be produced relatively easily by using non-invasive devices that deliver mechanical or electrical tactile stimulation. These stimulations can provide proportional feedback about a certain action. The sensory information provided can be valuable in describing what is occurring during the desired task, however one major issue is that this type of sensation typically results in increased response times caused by the locational differences between the perceived and actual sensation [7]. Somatotopically matched feedback has the advantage of being able to reduce the cognitive burden by providing a more natural sensation. Somatotopic matching techniques have been studied using both non-invasive and invasive techniques.

Non-invasive approaches are based on the process of naturally remapping the phantom sensation onto the residual limb [8]. The locations on the residual limb must be identified and labelled based on the perceived location on the phantom limb. Stimulation at these locations can be performed to activate sensory receptors beneath the skin to produce the desired sensation. The issue that arises with this process is that it can be time consuming to search and locate the location on the limb and in many instances is not achievable in all amputees [9].

Many current invasive somatotopically matched approaches are based on the implantation of electrodes onto peripheral nerves. These electrodes provide electrical stimulation to the afferent pathways located in the median and ulnar nerve providing the user with sensation throughout the hand. For example, Tan et al, using peripherally implanted cuff electrode, has shown repeatable and stable sensory responses in two human amputee subjects [10-11]. By regulating the location of the electrical stimulation and its properties, various sensation regions can be perceived with different types of sensation, such as light touch or tapping. These techniques have been successful in research practice, however, there are certain drawbacks including the need for invasive surgery, the extraneous post-surgery care, and the instability that may be present from long-term exposure.

In this preliminary study, we evaluated the feasibility of using transcutaneous nerve stimulation along the upper arm in eliciting haptic sensations [12]. Specifically, a custom array of electrodes was applied to the surface of the skin along the proximal upper arm (Figure 1). The electrodes delivered biphasic stimulation to pairs of closely-spaced electrodes creating a specific electrical field that activates the median and ulnar nerve and simulating sensation in different regions in the

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hand. The purpose of our current study was to evaluate the response that occurred when two pairs of electrodes were selected and stimulated simultaneously. The study also quantified whether the time delay between the dual stimulation has an effect on the sensation regions that are perceived. The selected electrodes will be stimulated multiple times to test the stability and repeatability of the perceived haptic sensation.

II. Methods

A. *Subjects*

We tested two neurologically intact subjects. During the study, modulated electrical stimulation was sent to the median and ulnar nerves of each subject through transcutaneous nerve stimulation. The electrical stimulation induced haptic sensation across their hands. Each subject gave informed consent via protocols approved by the Institutional Review Board of the University of North Carolina at Chapel Hill prior to any testing.

B. *Experimental Setup*

Subjects were asked to sit in a chair with both arms resting comfortably on a table. In order to induce sensation in the hand, the median and ulnar nerve bundles were activated by electrical stimulation via a 2x8 grid of electrodes that was placed along the medial side of the upper arm beneath the short head of the biceps brachii (Figure 1). This placement was used due to the fact that it provided the most superficial contact to the median and ulnar nerve fibers.

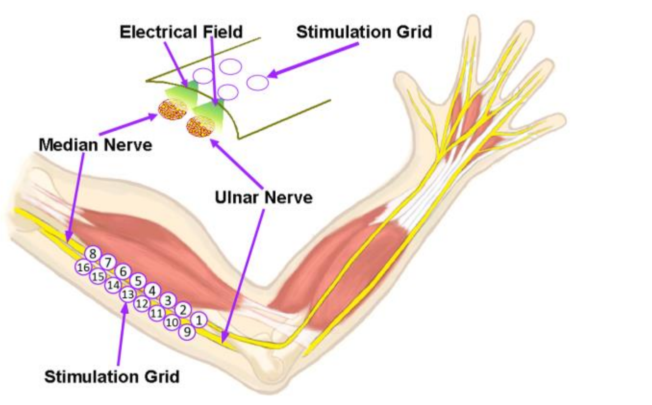

Figure 1: Diagram of 2x8 Stimulation Electrode Array placement on the upper arm. The array was applied just below the biceps brachii where the median and ulnar nerves are most superficial. A variable electrical field was produced, based on the pair of electrodes that are chosen and stimulated, activating different axons in the nerve bundles and in response providing haptic sensation to the subject.

The 2x8 electrode array allowed for the selection of different pairs to be used during stimulation. The various pairs produced diverse electrical fields that caused different groups of neurons in the nerve to be activated leading to sensation produced in different regions throughout the hand. Each electrode in the array was approximately 1cm wide Ag/AgCl gel electrodes.

The grid of electrodes was connected to the columns of a switch matrix (Agilent Technologies, Santa Clara, CA), while the rows were connected to the anode and cathode of a simulator channel. The multi-channel programmable stimulator (STG4008, Reutlingen, Germany) was used to deliver biphasic modulated electrical stimulation based on desired parameters, such as frequency, amplitude, and pulse width (Figure 2). Two sets of anode and cathode connections were made from the switch matrix to the stimulator in order to stimulate two pairs of electrodes simultaneously. A custom MATLAB (version 2016b, Natick, MA) interface was used to modulate the stimulation parameters and control the switch matrix.

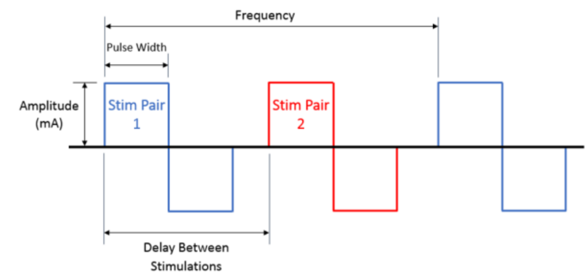

Figure 2: Biphasic square wave used during the stimulation of the Median and Ulnar nerve. The delay represents the time offset between the stimulation of the first pair and the stimulation of the second during the concurrent nerve stimulation.

A labeled hand map (Figure 3) was created and incorporated into another MATLAB interface allowing for the recording of the perceived region in the hand for each pair of electrodes. The locations were recorded by the experimenter as the subject indicated the regions where sensation was felt based on the displayed image. They were later asked for a final visual confirmation before the region data and stimulation parameters were saved. During the experiment, subjects were asked to limit substantial movements due to the arrangement of the equipment, however pressure applied to electrodes assured the placement of the array remained consistent throughout the study.

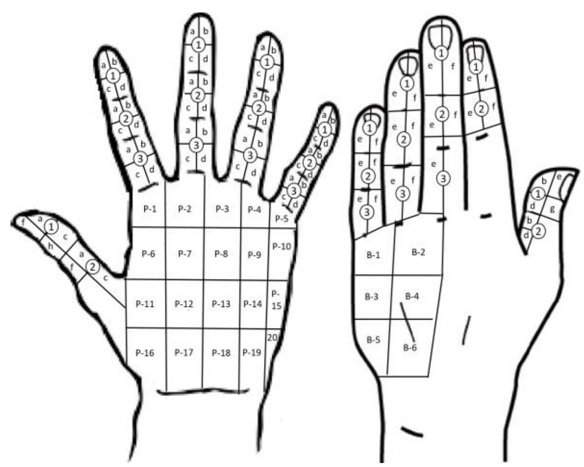

Figure 3: Label hand map that was used to help the subject identify and state where the perceived sensation was located on their hand during each stimulation and trial.

C. *Procedures*

The experiment began by initially searching through the pairs of electrodes to locate those that were reported as inducing sensation in the hand. The stimulation was delivered as a short, constant stimulus train. The stimulation duration, rest duration between stimulation, pulse width, and frequency were kept constant throughout the study with values of 2s, 1s, 200 µs, and 150 Hz respectively. These values were chosen based on a previous study that had been conducted [12]. The current amplitude of the stimulation was dependent on the individual subject but was keep constant among each subject's trials whenever possible. The current amplitude was adjusted that can produce sensation of smaller regions in the hand and was below the individual's motor threshold eliminating any possibility of muscular contractions along the arm or hand. The smaller sensation regions produced would allow for a better comparison of how the combination of single pairs affected the resulting sensation perceived in the hand. During the single pair testing, once the subject felt sensation in their hand, the location and pair of electrodes were recorded to be used during the double stimulation. The subject was asked to break the sensation felt into three categories; low certainty/low strength, moderate certainty/moderate strength, and high certainty/high strength. The levels of sensation strength were illustrated in later diagrams as being green for low, yellow for moderate, and red for high.

Double pair testing was broken up into three portions: the evaluation of the change in perceived sensation when combining the recorded electrode pairs, the evaluation of how the delay between the stimulation pair changes the sensation region, and the evaluation of the repeatability/stability of the sensation regions over time.

First, the evaluation of the change in sensation between single and double pairs was conducted by stimulating the double pairs and identifying the perceived sensation regions. The stimulation delay between the individual pairs was 3.33 ms for all the double pair testing during this portion of the study. A delay of 3.33 ms results in the second pair being stimulated directly between the pulses of the first stimulation pair.

Second, once 5 double pairs had been stimulated, a particular double pair was selected for evaluating how the delay between individual pairs affects the haptic sensation. The double pair that contained the most sensation regions throughout the hand was the one selected. The delays ranged between 0.5-3.0ms with steps of 0.5 resulting in 6 trials with delays of 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0ms offsets. For these 6 trials, the order of the time delay was randomized.

Third, to test the repeatability and stability of the double pairs, each of the 5 double pairs were stimulated and the sensation region was recorded two more times, resulting in 10 more double pair stimulations. After each double stimulation trial, the corresponding individual pairs were stimulated resulting in a total of 30 trials. For these 30 trials, the delay was set to 3.33ms to allow for comparison with the double pair stimulations tested in the first portion of the experiment. The time between trials of similar double pairings averaged around 20-30 minutes.

D. Data Analysis

The sensation regions that were seen in each trial were mapped to the corresponding location on the hand map in Figure 3. The double stimulations from the first portion of the experiment were matched with their corresponding single pairs and a visual comparison was done to evaluate the summation of haptic sensation. Similar double pairs and the 6 trials that varied the delay were bundled together and a visual comparison of the hand maps were evaluated for each.

III. Results

For the following diagrams, the colors in the hand map indicate where the sensation was felt by the individual and the intensity of the sensation in that region. Specifically, green represents sensation with low strength or low certainty, yellow represents moderate strength or moderate certainty, and red represents high strength or high certainty.

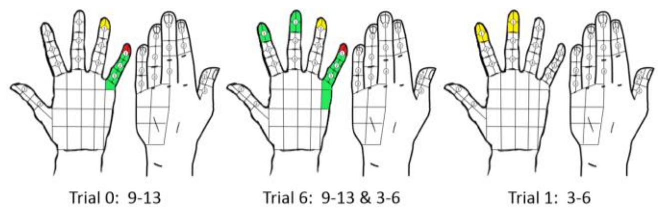

Figure 4: Comparison between the perceived sensation region during concurrent stimulation and the regions during the individual stimulation pairs. The left and right hand map are the individual pairs, while the center diagram is the regions identified during double stimulation. Green indicates low strength/certainty, yellow indicates moderate strength/certainty, and red indicates high strength/certainty.

Figure 4 shows one of the comparisons that were evaluated from the two subjects. When examining the three hand maps, the shaded regions showed a similarity as many of the sensation regions seem in the individual pairs appeared in the double stimulation, which indicated that a summation of the individual perceived sensations occurred during the concurrent nerve stimulation. New regions were perceived along with the change in strength of some of the locations. This is likely caused by the fact that the intensity of the sensation is subjective and may have affected how certain locations were perceived.

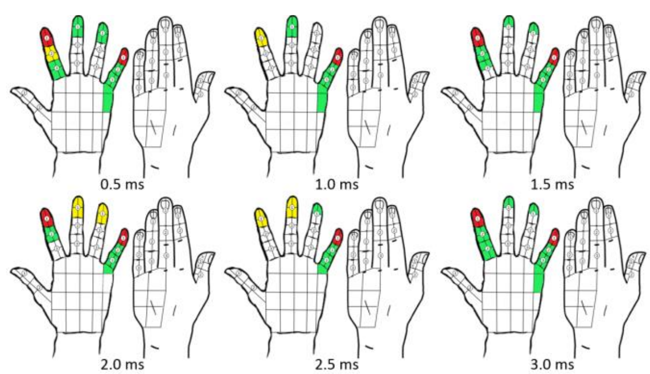

Figure 5: Diagram illustrating the effects of an alteration in the delay between concurrent nerve stimulations on the sensation regions perceived. The delays valued between 0.5-3.0ms in steps of 0.5ms. Green indicates low strength/certainty, yellow indicates moderate strength/certainty, and red indicates high strength/certainty.

The time delay during double pair stimulation was altered to determine if this parameter affected the perceived sensation region simulated in each subject. The results from subject 1 are seen in Figure 5 and illustrate similar results in the second subject. Based on the comparison of the hand maps, the delay appeared to have little to no affect the haptic sensation regions when the double pair of electrodes chosen remained constant. The certainty values were not considered during the comparison of varying delays, due to the fact that the certainty across trials was subjective as they attempted to compare the sensation to the strongest region at a given time.

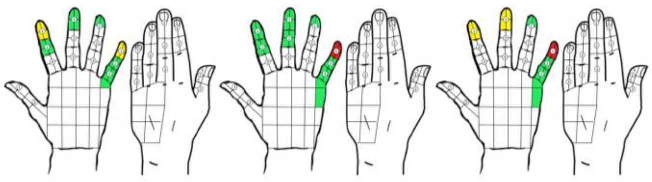

Figure 6: Diagram showing the repeatability and stability of concurrent nerve stimulation. The trials averaged around 20-30 minutes between similar double pair stimulations. Green indicates low strength/certainty, yellow indicates moderate strength/certainty, and red indicates high strength/certainty.

Repeatability and stability are important factors for ensuring that haptic sensation in the hand remains constant over time. When evaluating one set of double pairs, shown in Figure 6, the sensation region did not appear to change as the majority of the locations remain consistent. There was approximately 20-30 min between the first, second, and third trial showing that the sensation was repeatable after 60 min of recordings. Similar results are seen in both subjects and in the other sets of double pairs.

IV. Discussion

This preliminary study seeks to quantify the haptic sensation during concurrent stimulation at multiple locations of the peripheral nerves. The goal of the study was to address three questions about haptic sensation during concurrent nerve stimulation. The first question involved determining how the sensation region varied when stimulation was applied to two pairs of electrodes simultaneously. The results showed that the perceived region appeared to be mostly a summation of the regions seen in the corresponding individual pairs. When evaluating the double and single pairs, there were instances where new locations were felt, or old locations were lost during the double stimulation. This is likely due to the fact that many of the lost and gained sensation regions were identified as being low strength/certainty and may have been caused by an error or difference in subjective perception as the individual compares the strength to the strongest sensation felt at that time.

The second question involved determining how the delay between the concurrent nerve stimulation affected the region that was perceived by each individual. For both subjects, the sensation region appeared to remain consistent as the delay only slightly affected the sensation being felt at each instance. The results suggest that changing the delay between the stimulation pairs has little effect on the locations of sensation perceived.

The last question was to determine the stability and repeatability of the transcutaneous concurrent nerve stimulation. Comparisons between trials of similar double pair stimulations showed mostly consistencies in the sensation region perceived. Many of the differences in sensations reported were seen in the loss of “green” or low strength/uncertainty sensations or in the change in strength between trials. This is likely caused by the fact that the strength in sensation that the individual reports is based on a subjective representation of the pressure or feeling felt at a given instance. Overall, the results showed that concurrent stimulation appears to result in a summation of the individual sensation regions, that the delay has only a minimal effect on perceived sensation, and that the stability and repeatability is high during concurrent nerve stimulations.

One limitation of this current study is the small sample size used. This study was meant to be conducted as a preliminary experiment to evaluate the responses seen during concurrent nerve stimulation. In the future, it is intended that a larger sample size be tested in order to display a better overall representation. In doing so, statistical analysis will be conducted to illustrate the probability and effectiveness of the direct summation of individual pair sensations during double stimulation testing along with the probability of identifying new or a loss of regions. Statistics will also be done to show a quantitative comparison of the change in sensation with delay alteration and a quantitative comparison vindicating the stability and repeatability of this haptic sensation modality.

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