Quantitative Characterization of Haptic Sensory Adaptation Evoked Through Transcutaneous Nerve Stimulation

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Abstract— **Objective: Haptic perception is an important component of bidirectional human-machine interactions that allow users to better interact with their environment. Artificial haptic sensation along an individual's hand can be evoked via noninvasive electrical nerve stimulation; however, continuous stimulation can result in adaptation of sensory perception over time. In this study, we sought to quantify the adaptation profile via the change in perceived sensation intensity over time. Approach: Noninvasive stimulation of the peripheral nerve bundles evoked haptic perception using a 2x5 electrode grid placed along the medial side of the upper arm near the median and ulnar nerves. An electrode pair that evoked haptic sensation along the forearm and hand was selected. During a trial of 110-s of continuous stimulation, a constant stimulus amplitude just below the motor threshold was delivered. Each subject was instructed to press on a force transducer producing a force amplitude matched with the perceived intensity of haptic sensation. Main Findings: A force decay (i.e., intensity of sensation) was observed in all 7 subjects. Variations in the rate of decay and the start of decay across subjects were also observed. Significance: The preliminary findings established the sensory adaptation profile of peripheral nerve stimulation. Accounting for these subject-specific profiles of adaptation can allow for more stable communication between a robotic device and a user. Additionally, sensory adaptation characterization can promote the development of new stimulation strategies that can mitigate these observed adaptations, allowing for a better and more stable human-machine interaction experience**.

Keywords— Human-machine interface, noninvasive electrical stimulation, haptic perception, sensory adaptation

I. Introduction

Recent advancements in prosthetic technology can help restore motor deficiencies in upper limb amputees. Namely, myoelectric prosthetics can allow users to perform dexterous hand movements; however, these devices are often limited as they are unable to provide sensory information about a given motion or interaction. Haptic perception is an important aspect of human-machine interface users, as it may reduce cognitive burden during device use, increase device controllability, and promote a sense of body ownership [1]. Electrotactile stimulation can be used to generate haptic sensation when using a prosthesis. Stimulation of the median and ulnar nerves at the upper arm can evoke sensations perceived along an individual's phantom hand and forearm [2].

Stimulation can be delivered both invasively and non-invasively. While invasive stimulation approaches have shown great promise in research settings, electrode implantation requires surgery, which limits their translatability to widespread clinical populations. In addition, evoked percepts can lead to quick onset of fatigue based on the location of implantation [3]. Non-invasive stimulation through transcutaneous electrical nerve stimulation (TENS) can also elicit haptic sensation in the hand using electrodes placed on the skin surface. A stimulating electrode grid placed at the upper arm can generate haptic sensation in the fingers, palm, and forearm when placed against the skin near the median and ulnar nerves. TENS-users have reported sensory percepts, such as vibration, pulse, and paresthesia-like sensations at various regions on the hand [4].

Short-term stability has been reported, identifying that these evoked sensory percepts endure over time [5]; however, during continuous use, sensory perceptions may alter, leading to changes in sensation intensities over time. This phenomenon is known as sensory adaptation and occurs due to desensitization of nerve fibers, increasing the threshold required for haptic sensation detection [6]. Sensory adaptation is well documented for vibrotactile stimulation [7]. This form of stimulation results in both peripheral adaptation at the site of the stimulus along with central adaptation of the central nervous system. However, the course of adaptation is less understood for transcutaneous nerve stimulation techniques. Previous studies have characterized the decay rate of sensory percepts during invasive nerve stimulation; however, research studies have yet to examine the characteristic response during non-invasive upper limb TENS to the same extent [8]. During Graczyk et al., evoked responses resulted in sensory adaptation curves depicting decay time constants around 10-100 seconds [6]. Another research study performed by Buma et al. demonstrates a time constant of 30-200 seconds during TENS at the lower

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limb; although it should be noted that this study utilized non-continuous stimulation paradigms to evaluate delay adaptation [9].

II. Methods

A. Subjects

7 able-bodied participants (4 males, 3 females, 20-40 years old) were recruited from the Joint Department of Biomedical Engineering at UNC Chapel Hill and North Carolina State University for this study. All participants gave written consent through local Institutional Review Board-approved experimental protocols.

B. Experimental Setup

Participants were instructed to sit in a chair with their left arm propped in front of them. Their forearm rested against a padded table with their elbow forming a 135˚ angle. Prior to attaching the skin electrodes, an electrode prep pad and alcohol pad were used to clean the medial surface of the left upper arm. A 2x5 electrode grid was placed along the medial portion of the upper arm beneath the short head of the biceps brachii near the median and ulnar nerves. A multichannel stimulation device (STG4008, Multichannel Systems, Reutlingen, Germany) and a switch matrix (Agilent Technologies, Santa Clara, CA) were used to deliver electrical stimulation during each trial. Foam padding and a custom plastic vice was used to apply inward pressure to the electrode grid. The participant's right hand was positioned atop a force load cell (LCM201-100N, Newark Electronics, Chicago, IL) so their thumb could be used to apply graded pressure based on the perceived haptic sensations. A custom MATLAB® interface was used to perform electrode pair selection and augment the employed stimulation parameters. A pulse width of 200 µs and pulse frequency of 100 Hz were used for each trial [10]. A separate interface was used to record load cell output during the experiments.

C. Thresholding and Practice Load Cell Response

Sensation and motor threshold were determined before trials were performed. Establishing thresholds ensured that the employed stimulus evoked sensation without muscle activation in the hand or forearm, as this can lead to unwanted movement. A starting stimulation amplitude of 1.5 mA was applied. The amplitude was increased in 0.5 mA intervals until either a haptic sensation was reported in the hand or

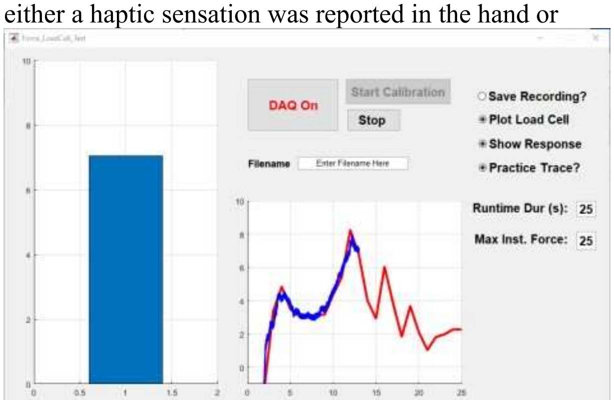

Fig. 1. Load cell MATLAB® interface. Instantaneous force feedback was shown through the bar graph on the left. Practice trace is shown on the right graph (red), with user load cell response tracing over in blue.

discomfort at the surface of the skin electrode. If no haptic sensation was reported, a new pair of electrodes was chosen, and the process was repeated. Once haptic sensation was reported in the hand for a given electrode pair, stimulation amplitude was increased in 0.1 mA intervals until either discomfort was reported or motor activation was observed in the participant's hand or wrist. This amplitude was recorded as the participant's motor threshold. To practice with the load cell, the second MATLAB® interface was used. A practice curve, as seen in Fig. 1, was displayed on the screen. When the interface timer was started, the output from the load cell created a trace that was overlayed on the initial practice curve. The bar graph in the interface also displayed the instantaneous force applied to the load cell. Without electrical stimulation, each participant was instructed to press down on the load cell so the trace followed the shape of the practice curve. This acted as a practice trial for participants to become acquainted with how physical force translated to the values displayed on the interface bar graph. It should be noted that the practice curve and trace were not displayed during the experimental trials.

D. Procedure

Trials lasted for 110 seconds, and each subject participated in 6 trials. A 3-minute rest period took place in between each trial to allow nerve reset. For each trial, a stimulus was delivered to the selected electrode pair with an amplitude that was 0.5 mA below each participant's motor threshold to prevent unintended muscle activation. During the trial, participants were instructed to press down on the load cell in conjunction with the intensity of the perceived sensation. They were instructed to use the bar graph feedback to quantify sensation.

E. Data Processing

To process the data, force recordings were imported into a MATLAB® script. Data was converted to a percentage of the maximum force input to better compare values across participants. All data per participant were averaged to create one adaptation curve. The fit() function with the 'exp1' fit model was used to calculate fit parameters to find the decay time constant τ for the exponential function represented by:

$$f(t) = a(1-e^{t/\tau})$$

III. Results

Sensory adaptation curves for non-invasive TENS were mapped for 7 able-bodied participants. Each participant performed 6 adaptation trials using the same electrode pair found during thresholding. Each trial used the same pulse width, pulse frequency, and pulse amplitude parameters. All participants reported haptic sensation in their left hand. The primary qualitative description was a paresthesia-like sensation at the fingers and palm. Some participants also reported slight sensation at the stimulation site, but these individuals reported that the generated haptic sensations had a higher intensity than the topical sensations.

All variation between participants was statistically significant with an alpha value of 0.05. It should be also noted that there was variation observed across trials for a single participant. 2 participants were chosen to depict variation observed between individual trials. All trials for Subjects 3 and 4 are displayed in Fig. 2. As seen below, both subjects display different approximate time constants for all 6 trials. Subject 3 also displayed large amounts of variation in perceived sensation. For some trials, namely trial 4, the subject experienced an increase in sensation after 50 seconds. Additionally, trial 1 experienced a steep decrease in sensation within 30 seconds of starting the trial, while trial 5 presented a gradual decrease in perceived intensity. Contrastingly, Subject 4's sensory adaptation patterns remained generally consistent, showing similar changes in perceived sensation during each of the 6 trials.

Fig. 3 displays the averaged adaptation curve per subject. As shown in the figure, Subjects 1, 2, 4, and 7 experienced stable sensation intensities prior to perceiving a decrease in sensation after approximately 20 seconds. While all subjects experienced an overall decrease in sensation, the rate of decay varied across subjects.

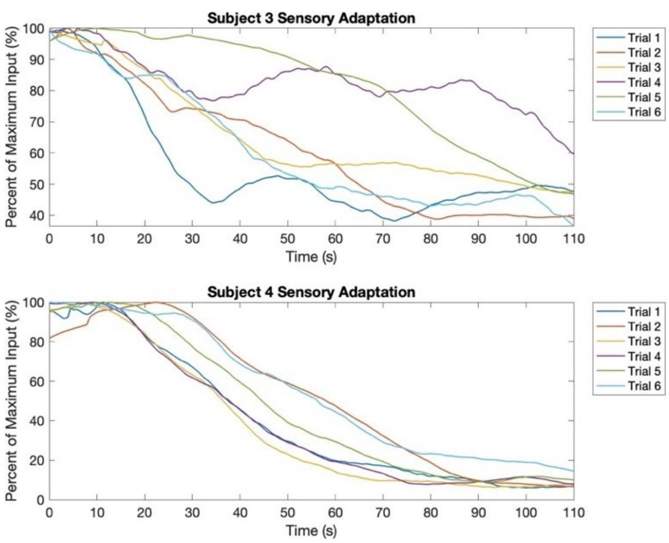

Fig. 2. Trials 1-6 for subjects 3 (above) and 4 (below).

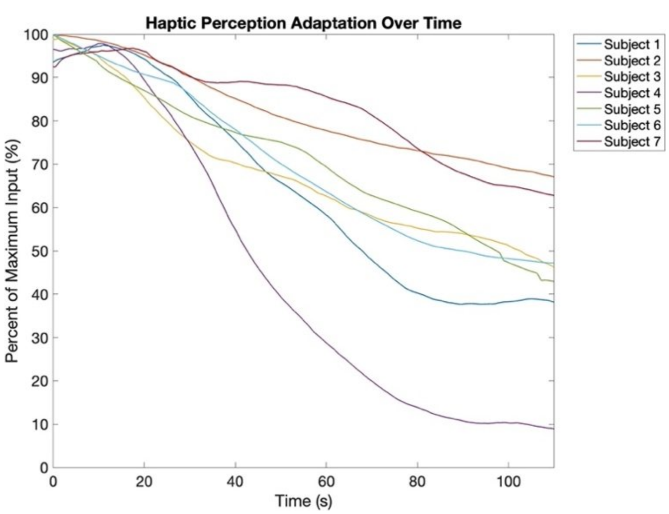

Fig. 3. Average sensory adaptation curves per subject.

Table 1. Adaptation Curve Parameters

Subject	Decay Rate (s)	R^2
1	93	0.9538
2	249	0.9836
3	141	0.9753
4	45	0.9464
5	145	0.9835
6	126	0.9840
7	251	0.9054

Interestingly, both Subjects 5 and 7 displayed an increase in perceived sensation between 35 and 60 seconds, a phenomenon that was not reflected in the other data sets.

Table 1 displays the decay rate time constants determined through the fit() function on MATLAB® along with the corresponding R^2 values. As seen in the table, Subject 4 had the lowest time constant at 45 seconds, which is reflected in the decrease in sensation between 40 and 60 seconds in Fig. 3. Subject 7 had the highest time constant at 251 seconds, which appears to match the approximately 5% increase in perceived intensity that delayed a decrease to 37% perceived intensity.

IV. Discussion

The purpose of our study was to characterize the adaptation profile of evoked haptic sensation through surface nerve stimulation. Our results show that a significant decrease in perceived sensation occurred across subject. As seen in the results, statistically significant variation was observed across subjects. It should be noted that this preliminary study only involved limited parameters. It is likely that gross movements across trials and changes in skin impedance during the trial could have affected perceived intensity across different trials. Additionally, it is likely that variation between data for a single subject can be attributed to the subjective nature of the effect of electrotactile stimulation. The actual intensity value recorded is slightly unreliable, as being able to discern between small changes in sensation intensity is very difficult.

To compare with previous literature on sensory adaptation characterization, unlike the findings in Graczyk et. al, most subjects did not experience a 50% reduction in sensation intensity after approximately 60 seconds. 2 of the 7 participants did not experience a 50% reduction in perceived intensity for any of their 5 trials. The patterns observed per subject more closely matched the 80% pain threshold curves depicted in Buma et. al, with perceived intensity reaching approximately 65%, like Subjects 2 and 7. However, each curve in Buma et. al shows an immediate decrease in perceived intensity, a pattern that was not consistent with the Figure 3 adaptation curves.

In the context of decay time constants, it is possible that slower decay rates in 5 out of 7 subjects compared to the 10-100 second findings in Graczyk et al. [8] are due to skin impedance decreasing stimulus amplitude reaching the target nerves. It is also possible that we observed faster decay rates in 5 out of 7 subjects compared to the 200 upper range time constant found in Buma et al. [9] is due to the use of continuous stimulation rather than of an intermittent stimulation approach.

There were several limitations in this study. First, the method of quantifying perceived intensity of haptic sensation was not ideal. To have continuous perceived sensation, we used a force transducer. The conversion from paresthesia-like sensations in the left hand to pressure from the right hand likely resulted in inaccurate perceived intensity measurements during a given trial. While a verbal response from each subject can likely be a more appropriate reflection of the subject's experience during a given trial, current intensity would be difficult to quantify as a percentage of initial sensation and rely on an individual's memory and subjective perception at a given time. A second limitation resulted in the variation found in Fig. 3. While the reported regions of activation in the hand were similar across subjects, it is likely that different portions of the median and/or ulnar nerve were stimulated, introducing a confounding variable for variation in adaptation curves. In addition, the use of an all-or-nothing recruitment of afferent pathways may lead to instability during activation. Altercation of the stimulation paradigms and profiles employed may help minimize variability across trials and subject; however, future work is needed to assess how these changes affect sensory adaptation responses. Lastly, this preliminary study was designed to be performed as an initial investigation into this phenomenon. The limited number of participants and trials is a shortcoming of this study that we hope to address in the future. Greater evaluation of the variability within and across subjects can help us comprehend and account for it. Currently, decay parameter trends are not as apparent. Differences in biological features across participants and the user's subjective perception of the evoked percepts can likely affect variability as it pertains to characterizing sensory adaptation responses; however, future investigations are needed to confirm this theory.

V. Conclusion

This preliminary study illustrates that sensory adaptation is evoked during the use of TENS in the upper arm and is similar to the response observed during TENS in the lower extremities and invasive peripheral nerve stimulation, with some variation in adaptation onset rates. A greater understanding of sensory adaptation can provide insight, promoting the development of strategies to combat sensory adaptation. These advancements can improve robustness and device longevity for future sensorized prosthetic systems. Specifically, it can promote the controllability of a person's assistive device and increase the amount of sensory information that can be accurately conveyed during continuous use.

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