EFFECT OF BIOMIMICRY ON PERCEIVED INTENSITY, NATURALNESS, AND PLEASANTNESS USING NON-INVASIVE ELECTRICAL STIMULATION

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ABSTRACT

This study focused on testing different non-invasive electrical stimulations for their perceived intensity, naturalness, and pleasantness. The eventual goal is to develop natural feeling, non-invasive electrical stimulation for prostheses. We found no difference between naturalness and pleasantness ratings; however, the 1st order biomimetic algorithms (amplitude or frequency modulation) felt stronger than the 2nd order (frequency modulation) stimulus while keeping the total charge constant.

INTRODUCTION

Limb-loss is a lifelong challenge with high-medical costs and often includes life-long use of painkillers, antidepressants, and other drugs. Up to 50% of upper limb amputees do not use their prosthetic [1], with their reasoning including high cost [2]–[4], ineffective controls [2], lack of sensory feedback [5], [6], and requires too much attention to control the prosthesis properly [7]. Invasive neurostimulation can provide a sense of touch with surgically implanted electrodes, but also comes with high-costs and surgical risks.

Electrocutaneous stimulation is similar to invasive neural stimulation in that it provides an intuitive form of sensory feedback with high spatial and temporal resolution [8]–[15]. Electrocutaneous stimulation has the added benefit of being inexpensive and compact; it can be readily implemented into commercial prosthetic sockets [14]. However, with traditional encoding algorithms the sensations feel unnatural, numbing or 'electrical' [16], [17]. Sharp, prickly sensations can occur at higher amplitude stimuli due to high electric field development at the edge of the electrode that are large enough to activate small, unmyelinated pain and itch fibres [18], [19]. The purpose of this research is to test non-invasive, biomimetic electrocutaneous stimuli and understand their effect on perceived intensity, pleasantness, and naturalness.

MATERIALS AND METHODS

Four different types of stimuli were tested: linear (i.e., amplitude proportional to applied force), 1st order biomimetic (amplitude modulation) [20], 2nd order biomimetic (frequency modulation) [20]–[22], and a combination of both amplitude and frequency modulation with 1st order biomimetic. Biphasic, pulsed stimuli were delivered using a MATLAB GUI and a custom high-compliance voltage constant current stimulator with updates to stimulation parameters occurring every 33 ms [23]. Participants first wet a small patch of skin on the upper arm where an electrode pad (1-cm diameter active electrode with a 0.75-cm diameter return electrode at each corner of a 9cm^2 quincunx pattern) was taped in place using Transpore™. A small dab of electro-gel was also applied to each electrode to ensure low-impedance connection.

Once connected the threshold of detection was identified using the method of ascending limits (2 second pulse train with 50µs pulse width at 150Hz). For the actual experiment, a 1.5-second force profile experienced during natural touch was played through each of the four algorithms. To ensure a fair comparison of intensity, the total charge for each type of stimuli was held the same using the 1st order, amplitude and frequency modulation algorithm as a reference (total charge depended on the individual threshold of detection and ranged from 12700 to 30700). For this algorithm, the amplitude varied between the threshold of detection and 6mA above the threshold, and frequency varied between 80Hz and 150Hz (all stimuli used biphasic pulses with 50µs for each phase). Using the total charge of this algorithm, the other stimulation parameters were modified to deliver a similar total charge. Linear had the frequency locked at 80Hz but amplitude varied from the detection threshold to the amplitude where the total charge equalled the reference. 1st order biomimetic set the amplitude range from detection to 6mA above and set frequency to the value that matched the total charge of the reference. The 2nd order biomimetic set the frequency range from 80Hz to 150Hz and set the max amplitude to the value that matched the total reference charge.

Each stimulation type was given three times in a randomized order. Participants were asked to rate each stimulation type on a scale of 1 to 10 for naturalness (0-"not natural" and 10-"very natural"), pleasantness (0-"I did not like this at all" and 10-"I really liked this"), and strength (0-"I did not feel the stimulation" and 10-"very intense"). The medians of the three ratings were normalized and then averaged across all participants and compared using a 1-way ANOVA and the Tukey-Kramer post hoc comparison ($p < 0.05$ for significance). Participants also selected from a list of descriptor words to describe how each stimulation felt. All procedures were approved by the Elizabethtown Institutional Review Board and consent obtained for each participant (5 individuals with intact limbs).

RESULTS

This data can be seen in Figure 1. Figure 1 shows the ratings for naturalness, pleasantness and strength of each type of stimuli. There was no statistical difference between stimulation types for naturalness and pleasantness. However, the 2nd order (frequency modulation) was significantly weaker than the 1st order (amplitude modulation) and 1st order (frequency and amplitude modulation). A heat map showing how frequently each descriptor word was used by the five participants can be seen in Figure 2. Linear and 1st order (frequency and amplitude modulation) appeared to have the most unnatural/electrical descriptors listed while 1st order (amplitude modulation) and 2nd order (frequency modulation) appear to have a wide spread of both natural/physical and unnatural/electrical descriptors depending on the individual.

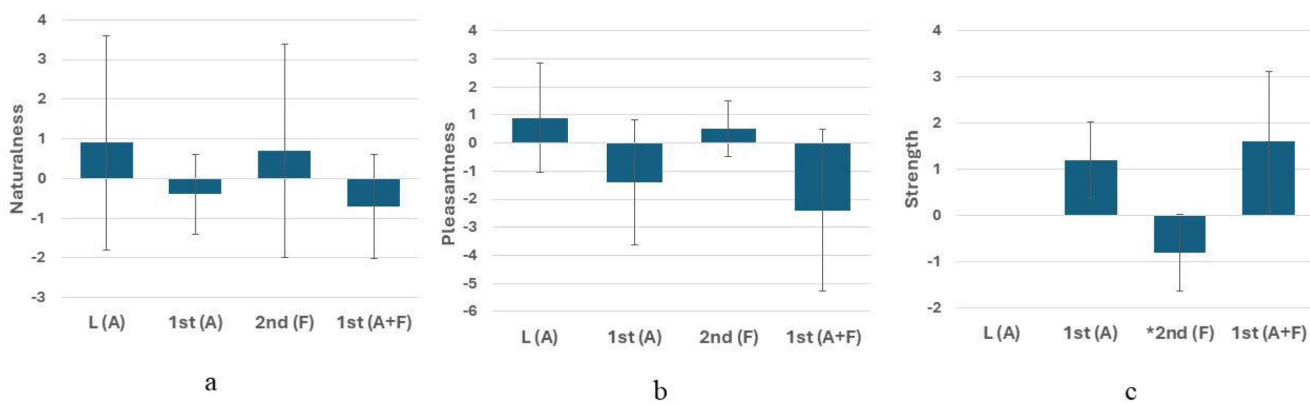

Figure 1: Normalized participant ratings for stimulus (a) naturalness, (b) pleasantness, and (c) strength for each stimulation type: linear (L, amplitude modulation); 1st order amplitude modulation (A); 2nd order frequency modulation (F); 1st order amplitude and frequency modulation (A+F). * Indicates statical significance indicated by 1-way ANOVA with Tukey-Kramer comparison, $p < 0.05$. Data are presented as the mean and standard deviation (both of which happened to be 0 for the normalized linear strength ratings).

DISCUSSION

We found that the 1st order biomimetic algorithms were perceived as stronger than the 2nd order algorithm even though the total charge delivered was the same. However, because the 2nd order algorithm only modulated frequency, it could also be that amplitude modulation feels stronger than frequency for the prototypical force profile played through each algorithm. Additionally, Likert data for naturalness and pleasantry show no statistically significant data that there is a difference between stimulation type. We expected that biomimetic algorithms might feel more natural than a traditional linear profile—however, the prototypical force profile included some elements of biomimicry (i.e., initial rapid rise on contact followed by a drop to a lower constant force during sustained contact) so the linear algorithm, which is proportional to the force, would have had some biomimicry as well. There may also be a trade-off between naturalness and strength as the 2nd order (frequency modulation) was the least strong and participants also used more natural descriptor words.

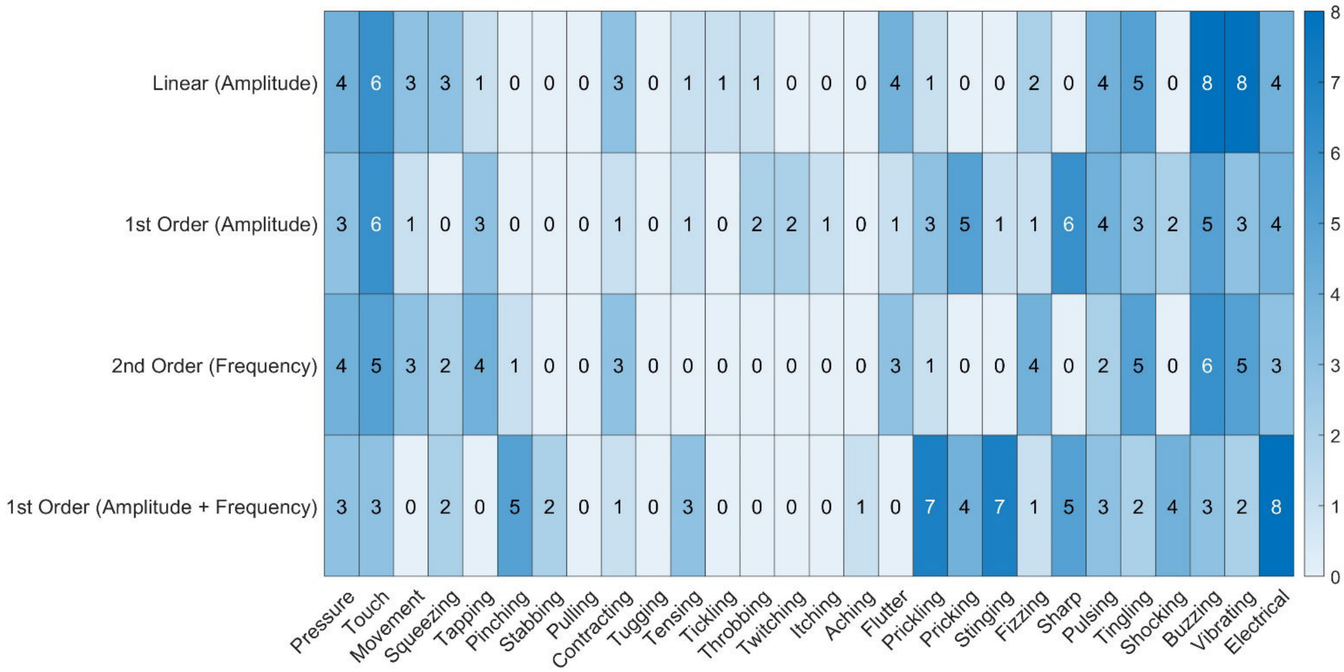

Figure 2: Number of times each descriptor word was used by participants for each stimulation algorithm. 2nd order algorithm had fewer unnatural and more natural descriptions.

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