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Inciting high fidelity tactile sensations using a single electrotactile electrode pair

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Abstract— **This paper investigates the possibility of inducing tactile sensations using electrotactile stimulation. The goal is to create several stimulus pattern feeling distinct enough for humans to differentiate them using only a single electrode. A single electrode is considered so that maximum fidelity of sensation can be achieved on parts of human skin with low receptor density in the dermis layer such as the forearm or abdomen. Two experiments were conducted on eight participants using a custom electrotactile waveform generator, a stimulation circuit, and electrodes. Experiment 1 investigates the possibility of quantifying different sensations induced by an electrotactile electrode. Experiment 2 investigates the ability of humans in identifying a number of different waveforms being sequentially played through a single electrotactile electrode pair. A confusion matrix was formed to analyze the ability of humans in distinguishing different waveforms. The results show an average sensitivity of 93%, specificity of 92%, precision of 98%, and accuracy of 94%. These results demonstrate that it is possible to produce distinguishable sensations using a single electrotactile electrode pair and electrotactile stimulation in general.**

Keywords—electrochemical sensor; point-of-care testing; wearable sensing, Wearable Biomedical Sensors & Systems.

I. INTRODUCTION

Numerous research efforts [1] and patents [2] aiming to utilize electrotactile displays have been produced as early as mid-20th century for in-demand applications such as sensory substitution for sight [3], feedback for prosthetics [4][5], sensory enhancement for VR/AR [6], and tactile feedback for touch panels [7], etc. However, many departed commercial endeavors that utilize electrotactile stimulation systems have been undermined by our lack of understanding of the human skin physiology and the limitations of electrotactile technology. These challenges could be resolved with the introduction of modern, powerful, and cheap microprocessors and sensors as well as a better understanding of skin physiology. Hence, there is a chance of creating new untapped markets for products utilizing elements of electrotactile displays.

The term electrotactile refers to evoking a tactile sensation on skin surface by passing an electrochemical current through layers of skin and activating tactile receptor afferent nerve fibers [3]. The electrotactile sensation could be qualitatively described as a tingle, itch, vibration, tap, pressure, pinch, pain, etc. Most electrotactile literature focus on specific areas of the body such as the tongue, lips, fingertips, and palm due to their high concentrations of tactile skin receptors. This trove of receptors in return allows for a trade-off, sacrificing spatial resolution to incite various tactile sensations such as pressure, vibration, tingle, etc. [6] and textures [8].

However, using areas with high concentrations of tactile skin receptors for constant daily feedback is obtrusive and inconvenient since humans use most of these body part on a daily basis. One solution is to focus on areas of skin that are less obtrusive such as the arm, abdomen, and back. Unfortunately, such areas suffer from a low concentration of distinguishable tactile skin receptors. The sensitivity of humans to tactile stimuli is roughly measured by two point discrimination (TPD) test [9]. The TPD for fingertips is almost four times smaller than that of forearms [10]. Hence, it is imperative to focus on achieving maximum sensations using a single electrode pair on lower TPD of unobtrusive skin locations, rather than using a large array of electrodes as presented in [11]-[8].

To this end, this paper is the first to demonstrate high fidelity sensations incited using a single electrotactile electrode pair. The goal is to have a high fidelity of tactile sensory stimulation using a custom single electrode pair in areas of skin that are less obtrusive and with low TPD. To achieve this goal, this paper describes the design and implementation of an electrotactile feedback system with a custom electrode pair and testing it by inducing a variety of electrotactile waveforms on eight participants.

II. METHODS

The methods and equipment used in this test can be classified in three sections: electrodes, current bearing circuit, and waveform generator.

A. Electrodes

The electrodes on skin surface play an important role in the quality of sensation received. An imperfect connection between the electrode and the skin may result in a painful experience. [12]. The skin surface area is not uniform in terms of its conductivity. current flow through a small low resistance region (probably sweat ducts, sebaceous glands, and minute epithelial breaks, 1-6 per mm2 skin area) will result in a painful sensation [12]. As a result, a curved electrode surface was opted for a flat one to avoid any defective connections. An array containing 23 electrodes, 8 anode/cathode and 15 ground, are fabricated on a standard PCB to realize the electrotactile stimulation as shown on Fig. 1. Only one of the cathode/anode electrodes are used for this work. The copper pads are connected to medical-grade stainless steel balls using

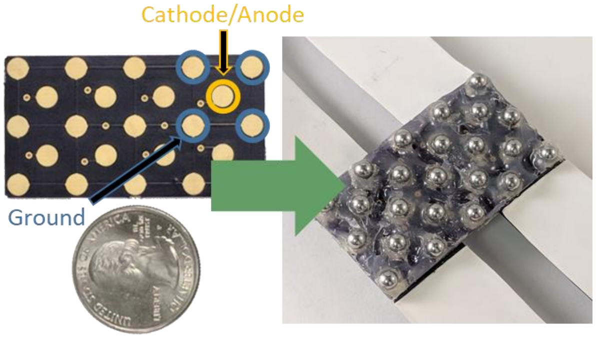


Fig. 1. The fabricated electrode array and the electrode pair used for this paper.

conductive silver epoxy paste and then covered with biocompatible epoxy layer. The electrodes are place on the left brachioradial muscle due to their smooth surface lacking any major nerve bundles that may affect the sensation.

B. Instrumentation

The instrumentation circuitry is composed of a classical voltage to current converter followed by a current mirror stage to steer the current into the electrodes as shown in Fig. 2. The waveforms generated on Op-amp1 input get played on a 1 kΩ resistor through Op-amp 1 feedback loop, creating a biphasic current that goes through the current mirror circuit and is reflected into the electrotactile electrodes. The electrodes are isolated from the current mirror circuit by a 0.1 µF capacitance. This is a part of an effort to minimize the risk of electrical shock and painful sensations in case of catastrophic system failure. There are sextuple layers of security that include supply and electrode fuses, 2 isolation capacitances, and two current mirror transistors. The isolation capacitances limit the total charge transferred to the skin in case of transistor and fuse failures as described in [13]. A supply voltage of ±100 V is necessary for making sure that the current mirrors can deliver the desired current to the high impedance load that is the epidermis layer without saturating. A Safety kill switch is prepared and placed next to test participant so that they can shut down the electrotactile induction in case of any inconvenience. The voltage waveforms are created by a national instruments NI USB-6259 controlled by a LabVIEW code. All circuit elements used are commercially available discrete components.

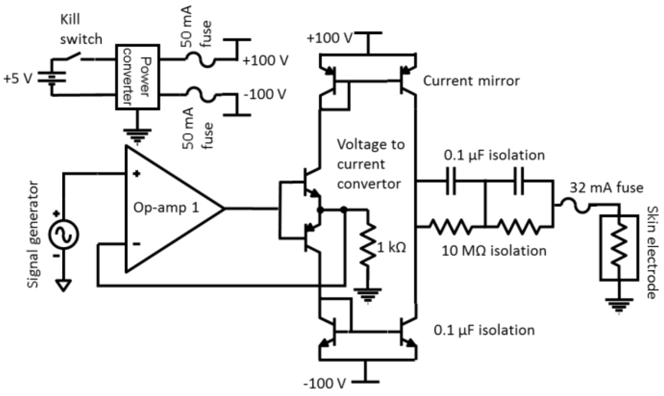


Fig. 2. The electrical circuitry used for realizing biphasic electrotactile currents.

C. Waveforms

The waveforms played on the skin are derivatives of simple symmetric and asymmetric charge neutral pulses as shown in Fig. 3 annunciated as style 1 and style 2. These waveforms are then repeated NS times and grouped into stimulation packs. The packs are divided by Inter Pulse Delay (IPD). The packs are repeated NP times and placed in a bundle. For some advanced stimulations, there may be multiple bundles, repeated NB times and separated by Inter Bundle Delay (IBD), called stimulation packs. Please note that parameters introduced in Fig. 3 only compose some of controllable dimensions of electrotactile sensing [13].

III. EXPERIMENTS

Two experiments are reported in this paper. The goal of first experiment is to prove that changing the parameters in an electrotactile waveform being played on skin surface would result in distinct sensations. The first experiment was to prove that changing parameters introduced in Fig. 3 would result in a change in the quality of sensation in a quantifiable way. Three waveforms were played on six participants and they were asked to answer a questionnaire regarding their sensation. The three waveform parameters are displayed on Table 1. These waveforms were continuously played on the participant's skin for 10 seconds. The participants were asked to describe their sensation in six categories of vibration, pressure, tap/pulse, tickle, pinch, prickly, itch and muscle on a scale from 1 to 5, where 1 being "no sensation" and 5 being "strong sensation". The standardized average of results of this

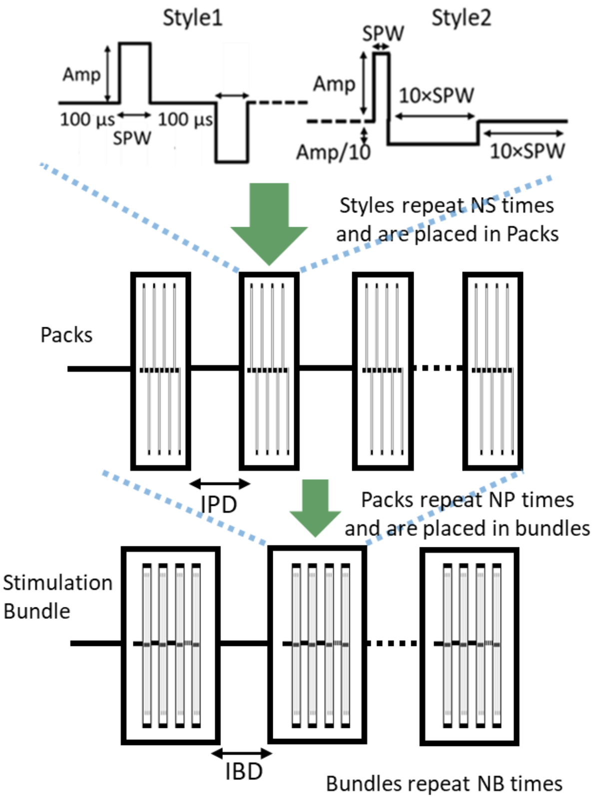


Fig. 3. Electrotactile waveform creation techniques used in this work.

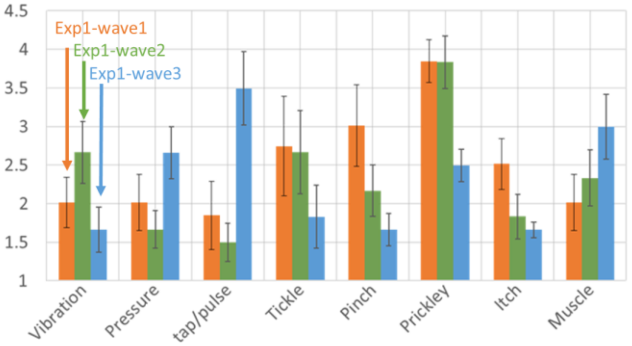


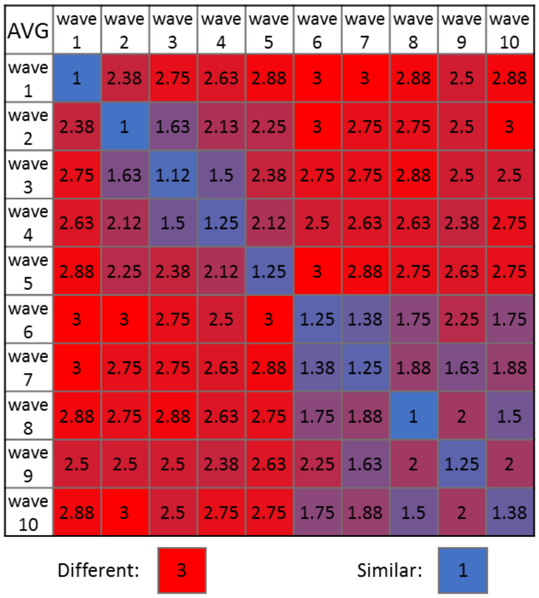
Fig. 4. The standardized average sensation quality reported by all 6 participants and the test standard error using repeated-measures ANOVA.

experiment over six participants and their standard error using repeated-measures Analysis of variance method (ANOVA) are shown in Fig. 4. This figure can be described as a spectrum of sensations that each of these waveforms create. The main distinctions that the subject get from waveforms 1 to 3 are prickly, vibration and tap which are qualitatively different.

The results acquired from experiment 1 beg the question: are humans capable of understanding and distinguishing the differences between a given set of waveforms? Experiment 2 was designed to answer this question. This experiment was run on eight adult participants, six males and two females between the ages of 18 to 50. Based on impressions from Experiment 1, ten distinct waveforms have been produced to answer this question. A brief description of each waveform is available in Table 1. Waveforms Exp2-wave 6, 7, and 9 are special cases. Exp2-wave 6 is similar to a ramp, starting with NS of 16 and IPD of 160ms and increasing NS eventually to 128, a strong sensation- and decreasing IPD to 40ms. Wave 7 is the exact opposite of wave 6, a ramp down function. Wave 9 is a string of continuous style 2 waveforms that increase incrementally IPD and decrease NS. The experiment procedure picks two of ten available waveforms from Table 1, plays one for 300ms and after a 1 second delay plays the other waveform for 300ms. Finally, the experiment asks the participant to rate how different the two waveforms felt: 1 for “exactly the same”, 2 for “slightly different”, and 3 for “completely different”. As a result, each participant will get the chance to compare each waveform with itself and all other waveforms. The average comparison results for all participants can be found in a heat map representation on Fig. 5. Ideally we wish for maximum deviation of 3 between two waveforms while having a complete match between the same waveforms, i.e. a complete diagonal blue line in the middle of an otherwise red square in Fig.5.

Table 1. The list of all waveforms being played on participant’s skin.

waveform	Style	SPW (μS)	IPD (ms)	IBD	NS	NP	NB
Exp1-wave1	2	250	50	NA	16	NA	NA
Exp1-wave2	1	50	12	NA	16	NA	NA
Exp1-wave3	1	50	450	NA	16	NA	NA
Exp2-wave1	1	50	14	NA	16	16	1
Exp2-wave2	1	50	40	NA	16	8	1
Exp2-wave3	1	50	95	NA	16	4	1
Exp2-wave4	1	50	160	NA	16	2	1
Exp2-wave5	1	50	10	NA	16	4	1
Exp2-wave6	1	NA	NA	NA	NA	4	1
Exp2-wave7	1	NA	NA	NA	NA	4	1
Exp2-wave8	2	250	5	50m	16	2	4
Exp2-wave9	2	NA	NA	NA	NA	448	1
Exp2-wave10	2	250	10	NA	16	8	1



AVG	wave 1	wave 2	wave 3	wave 4	wave 5	wave 6	wave 7	wave 8	wave 9	wave 10
wave 1	1	2.38	2.75	2.63	2.88	3	3	2.88	2.5	2.88
wave 2	2.38	1	1.63	2.13	2.25	3	2.75	2.75	2.5	3
wave 3	2.75	1.63	1.12	1.5	2.38	2.75	2.75	2.88	2.5	2.5
wave 4	2.63	2.12	1.5	1.25	2.12	2.5	2.63	2.63	2.38	2.75
wave 5	2.88	2.25	2.38	2.12	1.25	3	2.88	2.75	2.63	2.75
wave 6	3	3	2.75	2.5	3	1.25	1.38	1.75	2.25	1.75
wave 7	3	2.75	2.75	2.63	2.88	1.38	1.25	1.88	1.63	1.88
wave 8	2.88	2.75	2.88	2.63	2.75	1.75	1.88	1	2	1.5
wave 9	2.5	2.5	2.5	2.38	2.63	2.25	1.63	2	1.25	2
wave 10	2.88	3	2.5	2.75	2.75	1.75	1.88	1.5	2	1.38

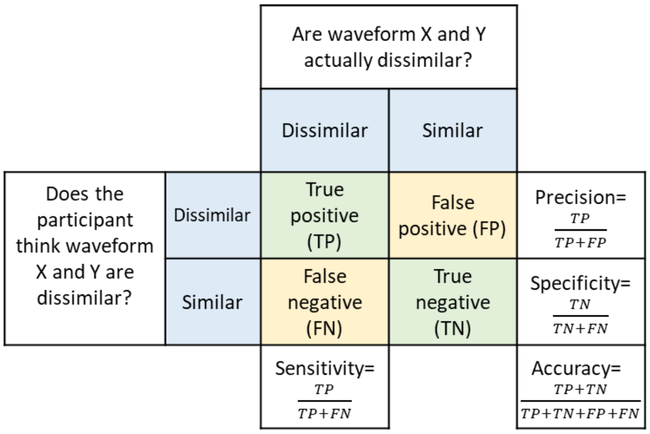
Different: 🟥 3 Similar: 🟦 1

Fig. 5. A heatmap representation of participant’s average response to comparing two waveforms.

To quantify the results acquired, a confusion matrix was formed to assess all participant’s ability to tell each waveform apart and shown in Fig. 6. Four key parameters were extracted from the confusion matrix:

- Sensitivity: how often do dissimilar waveforms get identified correctly
- Specificity: how often do participants correctly tell similar waveforms apart
- Precision: How good are participants at telling dissimilar waveforms apart
- Accuracy: The likelihood of participants predicting correct match or mismatch

Each waveform received a score regarding participant’s response. The average of these scores is a good indicator of



		Are waveform X and Y actually dissimilar?		
		Dissimilar	Similar	
Does the participant think waveform X and Y are dissimilar?	Dissimilar	True positive (TP)	False positive (FP)	Precision= $\frac{TP}{TP+FP}$
	Similar	False negative (FN)	True negative (TN)	Specificity= $\frac{TN}{TN+FN}$
		Sensitivity= $\frac{TP}{TP+FN}$		Accuracy= $\frac{TP+TN}{TP+TN+FP+FN}$

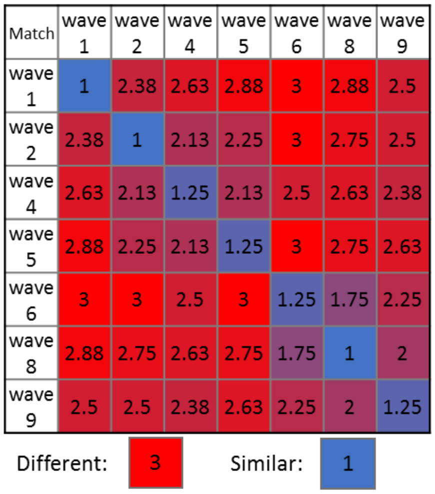
Fig. 6. A visual representation of the confusion matrix and its derivative parameter used in this work.

Table 2. The average confusion matrix results for all participants.

	wave 1	wave 2	wave 3	wave 4	wave 5	wave 6	wave 7	wave 8	wave 9	wave 10	AVG
Sensitivity	0.98	0.90	0.90	0.89	0.97	0.86	0.86	0.85	0.89	0.86	0.90
Specificity	1	1	0.86	0.75	0.86	0.75	0.75	1	0.86	0.75	0.86
Precision	1	1	0.98	0.97	0.98	0.96	0.96	1	0.98	0.96	0.98
Accuracy	0.98	0.91	0.9	0.88	0.96	0.85	0.85	0.86	0.89	0.85	0.90

the ability of all participant to tell waveforms apart. These results are shown in Table 2. It is possible to assert that while some waveforms lack in specificity, the participants were generally able to tell the waveforms displayed apart.

Taking a closer look at the results depicted in Fig. 5, it is possible to deduce that some waveforms were quite similar in sensation to others. Namely waveform 3 (Exp2-wave 3) to waveforms 2 and 4, waveforms 6 and 7, and waveforms 8 and 10. Obviously, not all alterations to waveform parameters indicated in Fig. 3 will result in a different sensation. Waveforms 2, 3, and 4 are the same style of waveforms bundled in NS 8, 4, and 2. Hence it is possible to claim waveform 3 is too similar in sensation to 2 and 4. The same can be said about wave 7 in regards to wave 6 and wave 10 in regards to wave 8. By omitting the dissatisfactory data, the heat map shown on Fig. 6 will turn into Fig. 7 the data presented on Fig.7 depicts a clearer image of a system with high distinction chances between each waveform. To confirm this, a new confusion matrix was formed with the refined set of data and displayed on Table 3. Using the refined set of data, improved all stats, bringing average specificity up from 86% to 92%.



Match	wave 1	wave 2	wave 4	wave 5	wave 6	wave 8	wave 9
wave 1	1	2.38	2.63	2.88	3	2.88	2.5
wave 2	2.38	1	2.13	2.25	3	2.75	2.5
wave 4	2.63	2.13	1.25	2.13	2.5	2.63	2.38
wave 5	2.88	2.25	2.13	1.25	3	2.75	2.63
wave 6	3	3	2.5	3	1.25	1.75	2.25
wave 8	2.88	2.75	2.63	2.75	1.75	1	2
wave 9	2.5	2.5	2.38	2.63	2.25	2	1.25

Fig. 7. A refined heatmap showing a better user performance by removing similar waveforms.

Table 3. Refined average confusion matrix results.

	wave 1	wave 2	wave 4	wave 5	wave 6	wave 8	wave 9	AVG
Sensitivity	0.98	0.92	0.92	0.96	0.94	0.90	0.94	0.93
Specifity	1	1	0.97	0.88	0.75	1	0.88	0.92
Precision	1	1	0.96	0.98	0.96	1	0.98	0.98
Accuracy	0.98	0.93	0.95	0.95	0.91	0.91	0.93	0.94

IV. CONCLUSION

This paper explored the potential to stimulate different sensations using a single electrode pair was asked. To answer, an electrotactile stimulation system was created and two experiments were conducted. Experiment 1 investigated the ability of one person to describe and classify different stimulations in 6 classes of Vibration, Pressure, tap/pulse, tickle, pinch, prickly, itch and muscle. This experiment indicates that changing parameters in waveforms result in tangible differences in perceived tactile sensation. Next, experiment 2 was performed to investigate if humans can tell two waveforms apart. A confusion matrix was formed to analyze the results which indicated that humans are indeed capable of distinguishing dissimilar and similar waveforms with high certainty.

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