Multi-Electrode electrotactile Stimulation to Combat Skin Dependency in Machine-to-Human Feedback

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***Abstract*— The advent of wearable sensing technologies has ushered the need for diversity of techniques to present information to users. This paper presents an electrotactile stimulation hardware and electrode array with the goal of presenting information to the user through the skin. The presented electrotactile stimulation device utilizes a distributed stimulation technique to prevent overloading the skin with electrotactile charges in case of a skin pore breakdown. An experiment was conducted to prove that a six electrode distributed electrotactile stimulation hardware and electrode presented in this paper would prevent skin pore overload in case of a breakdown. The results indicate that the six electrodes are capable of acting independently regardless of the skin resistance they observe.**

Keywords—Electrotactile; Augmentation technologies; wearable sensing;

I. Introduction

The gradual advancement of processing technologies both in cloud computing services and local processing units such as compute modules and microprocessors have created new margins for on-the-go computing and sensing. As such, there is an abundance of information that are readily available that could improve the lives of individuals if presented to them appropriately. Information pertaining to the user's health [1]–[3], social behavior [4], environment [5], [6], news alerts, etc. are some examples of information that can be used to augment human lives. Since the aforementioned information are presented to the user, in this paper they will be called machine-to-Human feedback (MHF).

The techniques used for MHF are influenced by the sensor type and the circumstances they are being used. For example, Fig.1 depicts a health monitoring system for at-risk patients. In this health monitoring system, MHF must be in constant communication with the user to prevent exposure or risky behavior while being discreet and un-obtrusive to prevent decreasing the quality of the patient's day-to-day life. From a neuroscience perspective and discounting direct brain stimulation, which requires highly invasive surgery [7], the only existing human-centered feedback methods are forms of sensory substitution that involve co-opting existing neural pathways for communication. Currently the predominant method of communication is through visual and audio cues, i.e. displaying messages on a smartphone screen or playing notification sounds, because these methods permit conveying complex information to the user. However, co-opting sight or hearing is disruptive to attention span and obtrudes daily cognitive activities. Studies have shown that audio and visual inputs require a substantial amount of human attention [8],[9], and over-reliance on these inputs may create attention deficiency and anxiety [10]. MHF literature supports alternative communication techniques, some of which include artificial tactile stimulation called electrotactile feedback [11]–[13]. Electrotactile MHF can provide information to the user through the largest sensory organ in human body -the skin- in an unobtrusive and discreet manner. Furthermore, studies have shown that tactile input is one of the least attention-demanding inputs to the human brain and can even improve focus and attention span in task related cases [14].

Despite the benefits of using electrotactile feedback, there are roadblocks to effective usage of electrotactile stimulation in day-to-day life. One such road block is the dependency of electrotactile sensations on skin hydration and the possibility of creating uncomfortable sensations due to over-stimulation of skin pores that act as current pathways [12]. Works in literature try to circumvent this complication by use of conductive gels and adhesive electrodes [15], [16], or using invasive microneedle electrodes that circumvent these pathways [17].

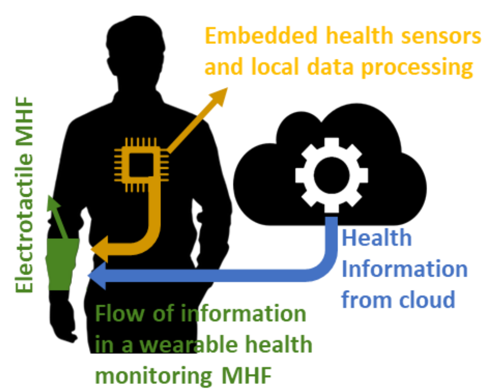

Figure 1. An example machine-to-human feedback (MHF) for real-time and unobtrusive feedback to a person in form of a wearable health monitoring system. The embedded health sensor and health information from the cloud are presented to the user in form of information-bearing electrotactile stimulations.

However use of adhesive gels is not preferable in day-to-day life and penetrating electrodes may cause skin lesions and infections [18].

Improving upon a previously reported setup [13], [19], this paper implements a multi-electrode electrotactile stimulation array with forced current distribution to prevent overloading skin pores that act as current pathways in case of pore breakdowns due to skin hydration deficiency. If successful, this technique would reduce the dependency of electrotactile stimulation on skin hydration, eliminating the chances of conducting noxious sensations and pave the way for a mainstream usage of electrotactile stimulation as a widely accepted method of MHF in human augmentation systems.

II. Distributed Electrotactile Stimulation

Electrotactile stimulation is conducted by evoking a tactile sensation on skin surface through injecting a controlled amount of electric charge into the dermis layer. Doing so will increase the voltage around myelinated afferent axons causing them to fire action potentials [20]. The key point that makes electrotactile stimulation possible is that the injected charge should be high enough to activate low-threshold tactile receptor axons in the dermis layer of the skin but not too high to activate high-threshold axons that are usually responsible for conducting noxious sensations such as pain, burn, itching, etc. [12], [21]. The somatosensory cortex of the brain treats action potentials created by electrotactile stimulation as if they were created by mechanoreceptors. Hence, electrotactile signals will be inferred as tactile sensations. Electrotactile stimulation can convey information to the person discreetly, with no onset delay or sound profile [22]. Electrotactile stimulation has been used for a variety of purposes such as prosthetic limb feedback and sensory substitution, rehabilitation, haptic surfaces, and a variety of other applications including VR/AR.

Electrotactile charges injected into the skin are in form of electrochemical currents that are conducted through pores in the epidermis layer of the skin in form of sweat ducts and epithelial breaks [23]. Because the density of sweat glands in the skin is 400-800 pores/mm2 [24], the current pathway through skin is spatially quantized and not uniform [12], [25], [26]. Under presence of electrotactile stimulation, especially if the skin is dehydrated, some of these pores may break down. A broken-down pore has a lower resistance and may conduct the majority of the charge that was meant to pass through all of the pores. Fig. 2(a) depicts this process under the presence of a large electrotactile electrode conducting a current of Iin. Because majority of charge travelling through a singular pore, a region of over-stimulation will be created that will activate high-threshold axons and cause noxious sensations [12].

If the electrotactile stimulation is to be independent of skin hydration, then charge buildup under a pore is to be avoided even in case of a pore breakdown. This can be done through utilizing a distributed electrode approach in which charge build-up is avoided by distributing the input current I_{IN} into smaller portions and forcing them into smaller electrodes called sub-electrodes (SE) in close proximity. Consequently, in normal operation mode, the distributed electrode acts as a normal electrotactile electrode delivering an overall current of Iin. However, in the case that a breakdown happens, the current going through the broken-down pore will be much smaller than I_{IN}. Fig. 2(b) depicts this concept with a hypothetical three-way distribution of I_{IN}.

Towards implementing the distributed electrode technique, an array of three distributed electrodes, each composed of six small stainless-steel SEs (1.0mm G10 440C Stainless Steel Balls) were mounted on a PCB board as shown in Fig. 3. Stainless steel balls were selected as electrode materials since 440C stainless steel does not introduce any non-native ions to the skin and the ovel shape of electrodes ensures uniform and comfortable skin contact [27], [28]. The mounting of stainless-steel balls on a flat copper-based PCB was challenging due to impossible adhesion between stainless steel and copper through conventional soldering techniques. As a result, vias with the same diameter as the stainless steel balls were created on the PCB array wherein the stainless steel balls were placed. The balls were connected to the PCB copper trace on the backside of the array with a silver epoxy paste as shown in Fig. 3. In the current array of distributed electrodes, each electrode is composed of six individual sub-electrodes and surrounded by twelve ground electrodes. An isolating sheet of plastic was placed in the front side of the electrode to prevent any skin contact with PCB copper layers while patterned openings on the sheet allowed stainless steel balls directly contact to skin. In order to prevent skin contact with silver epoxy, the stainless steel balls were mounted first and pressed against their housings

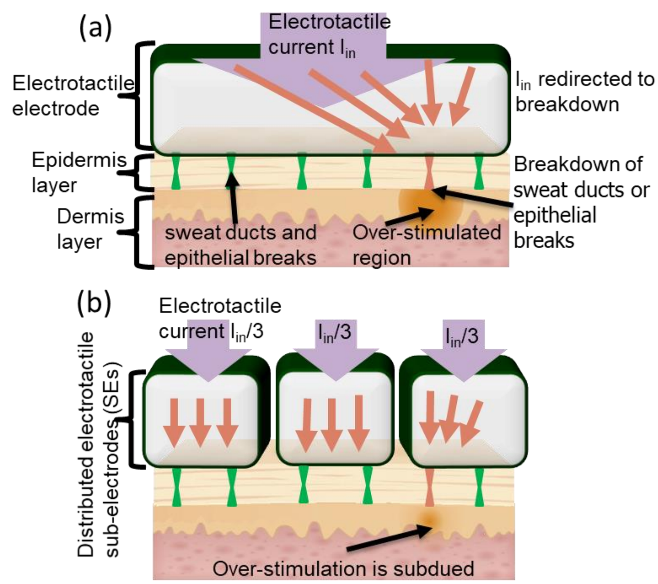

Figure 2: (a) The interaction between a large electrotactile electrode and skin pores that are susceptible for breaking down. A broken-down pore has a lower resistance and would redirect the majority of electrotactile current activating HTMR pain receptors. (b) The proposed concept of distributed electrotactile electrode prevents a broken-down pore from conducting the majority of electrotactile current. As a result, noxious sensations are not created due to charge accumulation under the broken-down pore.

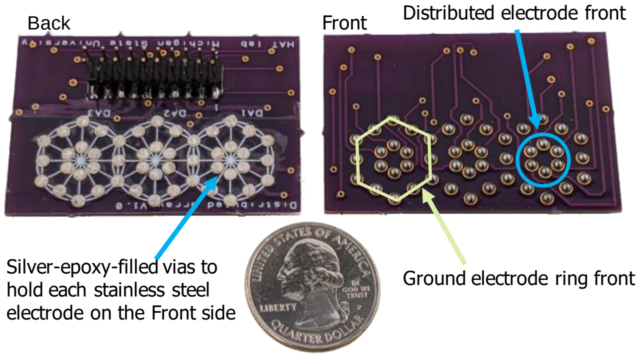

Figure 3: Fabricated 3 side-by-side distributed electrodes where each distributed electrode is composed of 6 SEs (1.0mm G10 440C Stainless Steel Balls) in a hexagonal pattern that are surrounded by 12 ground electrodes. The stainless steel balls were adhered and connected to the PCB board using silver-epoxy paste.

before administration of silver epoxy. The front side of the distributed electrodes were inspected with a microscope to ensure no silver-epoxy was present in the front side.

The instrumentation circuitry used to drive the distributed electrodes and to ensure true equal distribution between electrodes is shown in Fig. 4 composed of a classical voltage to current converter and a customized current mirror stage to steer the current into each SE in the distributed electrode. A bi-phasic electrotactile waveform is created by a PWM DAC and filtered and given to Op-amp 2. Op-amp 2 displays this bi-phasic waveform on a 1kΩ resistor Rf, creating a biphasic current that is replicated and reflected into the electrotactile electrodes by the cascode current mirror transistor families Qp and Qn. However, the current reflected by Qp2 and Qn2 see equal emitter resistance of Qp4 and Qn4 families regardless of the skin resistance of each SE. As a result, the current is equally distributed among all six SEs. The SEs are isolated from the current mirror through a 0.1µF capacitance as part of safety procedures to isolate the DC values between current mirror and SE to prevent noxious sensations in case of catastrophic system failure [29]. A supply voltage of ±80 V is necessary to ensure that the current mirrors can deliver the desired current without saturating to the high impedance load (typically 10-100kΩ [12]) that is the epidermis layer. The voltage waveforms are created by an ATmega32U4 DAC and filtered through a Sallen-Key low-pass filter as shown in Fig. 4.

III. Experimental Verification

To test the viability of the distributed electrode technique, a test scenario was devised to observe the ability of distributed electrotactile electrode to react to a sudden shift in the skin resistance value observed on SEs. An array of six potentiometers were assembled, each potentiometer displaying a resistance value of 10kΩ which is the nominal skin resistance under average hydration. These potentiometers act as an artificial skin for this experiment. Following precedent by [13], [19] a 2kHz biphasic pulse train of ±6mA was displayed on the artificial skin and the voltages on each electrode were recorded. The recorded voltage corresponds to the electrotactile current induced by the electrotactile stimulator circuit shown in Fig.4. If the current distribution of a ±6mA current is working properly, each SE should see a voltage of ±10V. Seven tests were conducted from which in tests 2-7 the resistor value of one of the SEs was dropped from 10kΩ to 500Ω to emulated skin pore breakdown. The voltages on all six electrodes were observed and recorded in Table 1. Test 1 is a test where all resistances seen by SE are 10kΩ which result in an observed voltage of approximately ±10V. Ideally, if the distributed current stimulator is operating properly, the resistance drop will not change the amount of current induced in the afflicted SE and the rest of the SEs. The results displayed on Table I demonstrate that a resistance drop on one of the SEs ,marked by the color yellow in tests 2-6, does not affect the rest of the SEs. Furthermore, the SEs that do not see a resistance change display similar behavior as their base state wherein no resistance drop was performed. These results confirm that the presented current distribution technique will prevent a

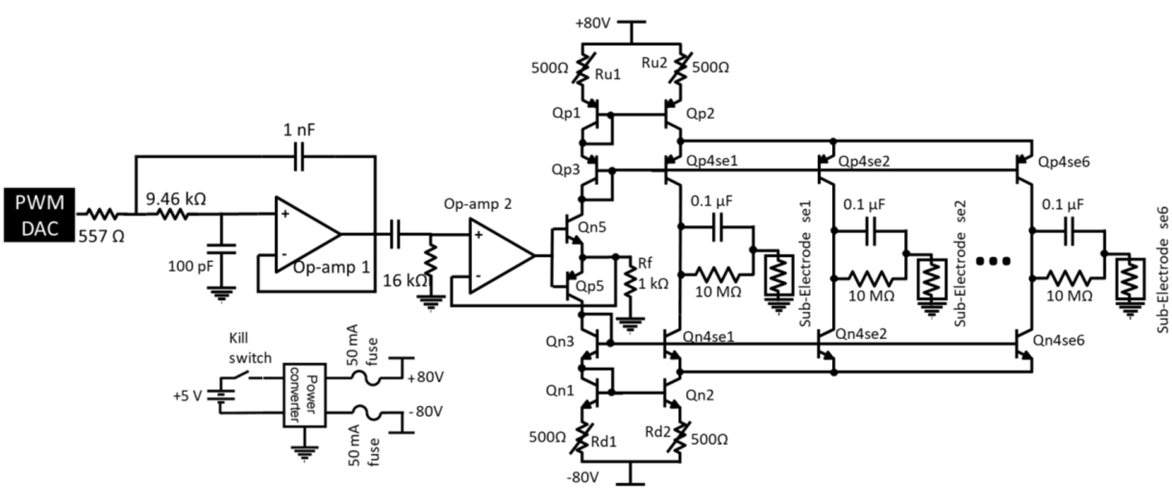

Figure 4: The electrotactile stimulation circuit schematic with current distribution for distributed current electrodes

Table 1: SE voltages of seven tests in which the resistance value seen by each SE is changed between a standard skin resistance of 10kΩ and 500Ω. The voltage value observed is indicative of the induced current on each of the six electrodes. The yellow boxes correspond to a resistance drop to 500Ω. Test 1 starts with all electrodes operating nominally and in tests 2-7 the resistance value under each electrode is dropped to 500Ω.

		test 1	test 2	test 3	test 4	test 5	test 6	test 7	mean	std
SE 0	postivie	10.06	0.49	9.90	10.12	9.99	9.79	10.07	9.99	0.11
	negative	-9.85	-0.47	-9.61	-9.71	-9.57	-9.52	-9.60	-9.64	0.11
SE 1	postivie	10.32	10.04	0.53	10.71	10.56	10.48	10.58	10.45	0.22
	negative	-9.98	-9.75	-0.51	-10.28	-10.14	-10.05	-10.15	-10.06	0.17
SE 2	postivie	10.54	10.25	10.27	0.55	10.13	10.24	10.19	10.27	0.13
	negative	-9.94	-9.76	-9.75	-0.54	-9.71	-9.70	-9.76	-9.77	0.08
SE 3	postivie	10.17	10.24	10.12	10.24	0.52	10.25	10.19	10.20	0.05
	negative	-10.12	-10.17	-9.85	-9.85	-0.52	-9.85	-9.90	-9.95	0.14
SE 4	postivie	9.92	9.91	9.99	10.16	9.76	0.51	10.11	9.98	0.13
	negative	-9.84	-9.79	-9.77	-9.82	-9.66	-0.50	-9.85	-9.79	0.06
SE5	postivie	9.92	9.89	10.22	10.07	9.89	10.05	0.56	10.01	0.12
	negative	-10.22	-10.11	-10.35	-10.15	-10.12	-10.21	-0.56	-10.19	0.08

saturation of skin regions experiencing pore breakdowns and possibly prevent noxious sensation.

IV. Conclusion

In this paper, electrotactile stimulation as a means for providing information to the user in an unobtrusive and discreet manner was presented. Electrotactile stimulation has the advantage of not expending as many attention resources as other non-invasive pathways to the brain such as sight and hearing. The shortcomings of electrotactile and especially its dependency on skin hydration and pore breakdown was discussed. A solution in the form of distributed stainless steel electrodes was presented and was accompanied with a modified electrotactile stimulator circuit with modified cascode current mirror structure. Experiments were conducted to emulate a pore breakdown and to gauge the response of current distribution electrodes and circuit. The results presented in Table 1 demonstrated that the current distribution technique presented in this paper is able to resume operations during a pore breakdown and has the potential to prevent noxious sensations.

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