

ElectricItch: Skin Irritation as a Feedback Modality

Henning Pohl

University of Copenhagen
Copenhagen, Denmark
henning@di.ku.dk

Kasper Hornbæk

University of Copenhagen
Copenhagen, Denmark
kash@di.ku.dk

ABSTRACT

Grabbing users' attention is a fundamental aspect of interactive systems. However, there is a disconnect between the ways our devices notify us and how our bodies do so naturally. In this paper, we explore the body's modality of *itching* as a way to provide such natural feedback. We create itching sensations via low-current electric stimulation, which allows us to quickly generate this sensation on demand. In a first study we explore the design space around itching and how changes in stimulation parameters influence the resulting sensation. In a second study we compare vibration feedback and itching integrated in a smartwatch form factor. We find that we can consistently induce itching sensations and that these are perceived as more activating and interrupting than vibrotactile stimuli.

CCS Concepts

•Human-centered computing → Haptic devices; Empirical studies in HCI;

Author Keywords

Itch feedback; haptics; wearables; on-body interfaces; skin

INTRODUCTION

Our bodies are able to steer our attention in diverse ways. We shiver/sweat when our body's temperature moves outside a normal range. We yawn and our eyelids feel heavy when we are tired. All these are natural ways to prompt us to make a change, like going to sleep. Yet, the ways our devices notify us do not tap into this repertoire of natural feedback mechanisms.

Instead, our devices blink and vibrate to get our attention. While we perceive these messages *through* our bodies, they remain artificial and external in nature. Just as natural user interfaces are designed with input that make use of the inherent expressiveness of the body (e.g., full body gestures) [32], we argue that feedback as well should align with the body. Hence, we explore using *itching* as a feedback modality in interactive systems. Itching is one of the body's natural attention-capturing mechanisms. According to Eccleston, it nudges us to pay attention to our skin, possibly to reinforce grooming behavior [9], making it a good candidate for feedback.

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than the author(s) must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from permissions@acm.org.

UIST'18, October 14–17, 2018, Berlin, Germany

© 2018 Copyright held by the owner/author(s). Publication rights licensed to ACM. ISBN 978-1-4503-5948-1/18/10...\$15.00

DOI: <http://dx.doi.org/10.1145/3242587.3242647>



Figure 1. We explore skin irritations, such as itching, by means of electrical stimulation for use as a feedback modality. The sensations generated with this method range from gentle and soothing ones all the way to stinging and irritating ones. Compared to vibrotactile feedback, itching grabs attention more and increases the urge to react.

Because of the way itching is already used by the body it is a relatively unpleasant sensation compared to other feedback modalities. While this makes it less suitable for communicating some types of feedback (e.g., incoming birthday wishes), this property can be desirable for other scenarios. For example, creating discomfort is a way to nudge users towards completing tasks they might otherwise procrastinate on (e.g., filing their taxes), or can be a part of storytelling [2]. An additional benefit of itching is that it is closely linked to the action of *scratching*. Hence, not only does it capture our attention, it also nudges us to move our hand to the affected location—a property valuable for interactive systems that not only aim to notify a user, but to also elicit a response.

In this paper we investigate itching as a feedback modality. Starting with an overview on the sensation of itching, we then focus on electrically generated itch sensations. We present a custom stimulator design to induce itching sensations. In a first user study, we used this device to gather qualitative experience ratings for a wide range of stimulation signals from 12 participants. Our results show that our device induced itch sensations, but also activated several other electrotactile sensations, from gentle soothing to intensely irritating ones. In a second study with 14 participants, we narrow the sensations to only itching and compare it against vibrotactile feedback. We show it is possible to consistently create itching sensations and that they are more interrupting and activating than vibrotactile stimuli. We also asked participants to indicate preferences for 10 notification scenarios and find that itching is the preferred modality when in more somber situations, such as during work or when in traffic.

RELATED WORK

While we explore itching as a feedback modality for interactive systems, there is previous work on itch in other fields, primarily medicine and psychology. Itch feedback uses the skin as an output surface and thus also relates to previous systems similarly appropriating the skin for input and output.

Itching

A comprehensive overview of the sensation of itching was provided by Eccleston [9]. Three aspects are particularly interesting in the context of interaction: (1) The function of itching is partly to promote skin awareness (as part of hygiene behavior), guiding our attention and in fact our hands (to scratch) in order to self-groom. (2) Itching is socially contagious and the awareness it raises about the self also heightens said awareness in others. (3) The act of scratching can actually be pleasurable and thus there is an inherent reward system to promote self-grooming actions. These aspects underline the potential of itching for capturing attention.

The connection between itching and scratching was explored by Hall [14], who noted: “Itches don’t describe some state of the body at the felt location. Rather the intentional content of an itch is an imperative: ‘scratch!’” Eccleston also stated that, “you can’t have an itch without the notion of scratching being present — it’s built into the itch experience.” As reported by bin Saif et al., itch-induced scratching can even lead to pleasure [3]. They found a significant correlation between itching intensity and pleasurability of scratching. This might partly be due to the itch relief that is achieved by the scratching.

Previous work describes multiple ways of artificially evoking itch sensations (for an overview see, e.g., [15]). For example, Fukuoka et al. showed how mechanical stimulation of skin hairs on the face could trigger an “intense pure itch” in study participants [12]. A common approach is biochemically-induced itch, such as via histamine (e.g., used in [17, 43, 44, 54, 60]) or other substances [55]. Itching can also be evoked psychologically, for example, using visual stimuli. Showing people pictures of bugs or skin conditions [30], or videos of others scratching themselves [44] can induce itching. Yet, these methods are not easily integrated into or suitable for interactive devices.

A more suitable approach is to use electric stimulation to evoke an itch response. As early as 1943, Bishop reported that electrical stimulation can have this effect [4]. He experimented with direct stimulation of receptors in the skin via a “small electrical spark” from a high voltage (3000 V) stimulator. Other examples of early explorations of electrically-induced itch are works by Shelley et al. [53] and Tuckett [60].

With electrical stimulation, experimenters were consistently able to generate itching sensations in their participants. For example, in Tuckett’s study, 22 out of 24 participants reported itching sensations and a wish to scratch the stimulated area. Other studies confirming this kind of effect include Edwards et al. [10], Ikoma et al. [17], and Ozawa et al. [43]. Others, such as Tashiro and Higashiyama [59], have shown that this kind of stimulation does not only create itching sensations, but in fact can result in a wider range of stimuli.

With electrical stimulation, it makes a difference where a stimulator is attached. For example, Tuckett reported that he could evoke itching sensations on hairy skin, but not on glabrous skin [60]. He noted that this is likely due to the type of available nerve endings depending on the kind of skin. We can thus expect variance due to electrode placement, but also due to individual skin differences.

Skin-Based Input & Output

Integrating interactive devices with the skin has seen strong interest [56]. On-skin circuitry can be used to sense touch, trigger mechanoreceptors, light up LEDs/thermochromic pigments, or transmit data [21, 22, 24, 31, 62]. In addition to electronics, on-skin interfaces can also be biochemical [6]. For example, Bandodkar et al. developed a tattoo-like sensor that measures glucose levels in the skin [1]. Both chemical and electronic approaches could be used to build itch feedback stimulators. For this paper we built a conventional prototype that connects to standard electrodes.

Where we focus on output on the skin, this could be coupled with one of the many approaches for on-skin input. Examples of such systems are *SkinTrack* [63], *AuraSense* [64], *SenSkin* [42], or *Sound of Touch* [38]. By combining on-skin input with output, complete interactive systems can be realized, such as in Laput et al.’s *Skin Buttons* [28].

Where tattoo- or projection-based feedback uses only the surface of the skin, itching works *within* the skin. This is similar to the *ScatterWatch* system [46], where the transmissive properties of the skin are exploited to create glowing auras of light *inside* the skin. However, in contrast to glowing light, itching is not observable by others.

DESIGNING AN ITCH STIMULATOR

We chose electrically-induced itch as the most suitable approach. Generating itch sensations this way requires an electrical stimulator as well as tuning of the electrical signal for itching. Apart from the signal parameters itself (see Figure 2), electrode size, type, and placement also have an influence on the properties of the feedback (see, e.g., [20, 49] for early overviews of work on electrical stimulation of the skin).

In previous work outside HCI, higher signal frequencies were commonly reported to increase itch intensity. For example, Tuckett reported an increase of intensity for frequencies between 2–40 Hz [60]. However, for 100 Hz stimuli, this relationship ceased. More recent work by Ikoma et al. found similarly increasing intensity up to their tested maximum of 200 Hz [17]. On the other hand, Edwards et al. [10] used only 50 Hz signals and Ozawa et al. [43] only tested 5 Hz ones.

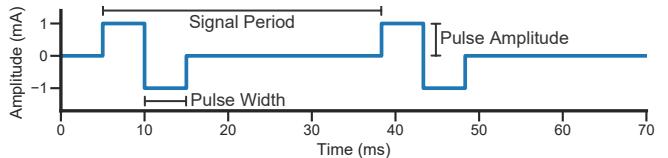


Figure 2. The stimulus signal we use for itching sensations is a biphasic square wave. We vary the signal frequency (period), pulse width, and pulse amplitude. Shown here is a 30 Hz signal with 1 mA pulses of 5 ms duration (10 ms for both phases).

The pulse width of the signal, together with the amplitude, defines the amount of power transmitted. Ikoma et al. found an increase of itch intensity with increasing pulse duration (0.08–8 ms) [17]. Other studies only used constant levels of pulse width. For example, Edwards et al. only applied 10 ms pulses and achieved good results with that [10].

Larger signal amplitudes have generally corresponded to stronger itch sensations. However, at some point the intensity of itch goes down and pain takes over as the dominant sensation. For example, in Ikoma et al.’s work, this point was at 0.12 mA [17]. Tashiro and Higashiyama reported a maximum for itch intensity at around 0.3 mA [59].

These previous results show that there is no clear prediction of what sensation or what strength an electrical stimulation will induce. The required parameters change with the study setup and influence each other. Furthermore, there are participant differences that can influence how a signal is perceived. Yet, the previous work provides a rough range in which we can search for the desired sensations. In this paper, we thus restrict our study of electrotactile sensations to signals of around 50 Hz, with a duration between 2–5 ms, and amplitudes under 1 mA. Note that within this parameter range we are not performing electric muscle stimulation where the goal is *actuation* of users.

Hardware Design

To generate electrically-induced itch sensations, we need a stimulator that is able to provide signals in the range described above. Such a device should be small, to allow for wearability, safe during use, and allow for easy and flexible external control.

There are a number of existing designs for functional electric stimulators in the literature. Such devices are sometimes described as *transcutaneous electric nerve stimulators* (TENS), other times as *electric muscle stimulators* (EMS), primarily dependent on their intended application area. All those systems generate an electric signal that is routed through the body via electrodes. Designs can also be distinguished by their waveform (monophasic or biphasic), the possible pulse lengths, the output mode (constant current or constant voltage), and their amplitude range.

Stimulators can be designed for high stimulation voltages [47], which also allows for high stimulation currents [34, 51]. Itching only requires lower currents and thus more basic designs can be used. We base our design on a boost converter and h-bridge combination already used successfully in previous work [8, 16, 57, 58, 61]. Where we use a constant current source for current regulation (similar to [7, 50]), more efficient closed-loop designs are possible [36].

In general, electrical stimulators are fairly commoditized and TENS/EMS units, such as the *prorelax TENS + EMS Super Duo*, are available without restriction for self-treatment of aches, muscle training, or relaxation of tensions. Furthermore, many gyms offer EMS-based training, while some spas offer TENS treatments. Some of these units are certified as medical devices, but many others only come with, for example, more limited CE certificates.

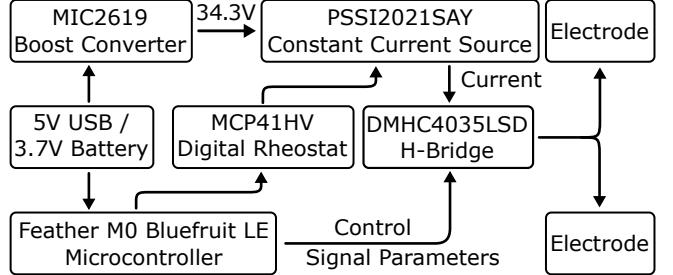


Figure 3. In our itch stimulator design, the battery voltage is first boosted to 34.3 V. A constant current source then regulates the voltage down again to a level respective the amount of skin resistance. The desired current is set via an attached digital rheostat. The device can be controlled via either a serial connection or via Bluetooth LE.

Functional electric stimulation devices are already available to, and in use by, the general public. Correspondingly, they are considered sufficiently safe for unsupervised use by non-experts, for example, for workouts. However, for research purposes such off-the-shelf devices are lacking in flexibility and level of available control. Yet, research prototypes can achieve similar levels of safety, by adhering to the best practices followed by these devices. However, note that non-conformant use (e.g., wearing electrodes over the heart) of such devices can still pose a risk.

The schematic of our itching stimulator design is shown in Figure 3. Our circuit is designed as an add-on board to an Adafruit *Feather* microcontroller. This allows for easy prototyping and for wireless control (Bluetooth or WiFi) of the stimulator during deployment. Similar to Steward et al. [57], we use an h-bridge for the output stage. As in most of the previous designs, we also use a boost regulator to create a stimulation voltage higher than the battery voltage.

In our circuit, the nominal 3.7 V from the battery or 5 V from USB are boosted to 34.3 V by an *MIC2619* regulator. The built-in overvoltage protection is configured to make sure no voltage higher than 35.0 V can be generated at this stage. Instead of tuning the output of the boost converter directly, we pass the signal through a *PSSI2021SAY* constant current source. This allows us to select the desired output current directly via an attached *MCP41HVX* digital potentiometer.

To guard against any potentiometer error, a fixed resistor is put in series. A 300Ω resistor, for example, ensures the maximum possible current after this stage would be 2.065 mA. At the output stage, the signal is passed through a *DMHC4035LSD* h-bridge. The final biphasic signal is then created by the microcontroller switching the h-bridge configuration.

Figure 4 shows the final board design and size. As described above, this design includes several components to ensure the generated signal is limited to safe current and voltage levels (see [26, 48] for overviews of applicable safety considerations). We also added an option to supply the voltage to the current source externally to enable operating the stimulator from a benchtop power supply. A second connector also allows using an external resistor setup for current control. This can, for example, be used to manually control the amplitude with a potentiometer during prototyping.

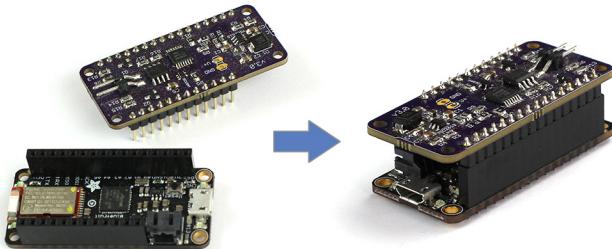


Figure 4. Our functional electrical stimulation prototype is designed as an add-on board to the Adafruit Feather series of microcontrollers. The two snap together to form a compact stimulator device that can be powered via battery or USB and can be controlled via a serial connection or a Bluetooth LE interface.

Previous work in HCI has often attached to off-the-shelf EMS units. For example, the *openEMSstim* toolkit¹ attenuates incoming EMS signals from such units. This results in much larger setups, which limits their suitability for in-the-wild studies or integration into small devices like wearables. Furthermore, not having full control over the generated signal limits how much of the functional electrical stimulation design space can be explored. The *openEMSstim* toolkit was also not designed for the much lower current signals we are interested here. We hope that by making our design and code available², this can benefit other researchers interested in functional electrical stimulation.

Our system can attach to any pair of output electrodes via a standard header connector. Potentially, our stimulator could be combined with more complex electrode grids to more precisely control where the signal is applied. Examples of such systems are Keller et al.’s [23] or Franceschi et al.’s [11] flexible electrode matrices, but also Nathan’s early electrode belts [39]. More complex activations could be achieved by adding multiple output channels to the stimulator (such as in [19]).

LOCATING AND QUALIFYING ITCH SENSATIONS

As we have described above previous work has reported a range of parameters that might induce itching, but there is no consensus on the exact signal setting to use. Furthermore, the parameter space for electrical stimulation is complex and sensations other than itching are likely to also be induced. The parameter space is also large and testing of every possible setting hence not feasible (although interactive exploration of such spaces has been shown to work [45]). A first task thus is to determine suitable stimulation parameters for itching.

In our first study, we focus on two main questions:

Q1 Which stimuli induce the sensation of itching?

Q2 What are qualitative properties of itching sensations?

Previous work in the medical field commonly concentrated only on perceived levels of itch and pain. We map a larger set of sensations in that space in order to determine the relationship of itching to other sensations. In addition to locating itching sensations, we also gather qualitative feedback on them and the other perceived sensations.

¹<https://github.com/PedroLopes/openEMSstim>

²<https://github.com/henningpohl/itch-feedback>

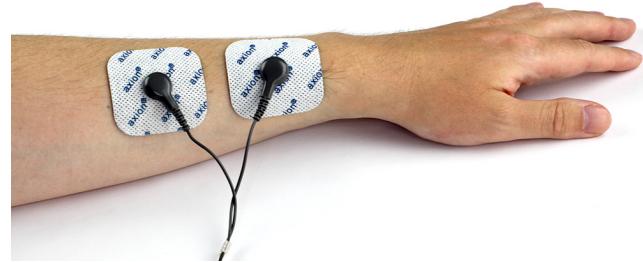


Figure 5. During the first study our participants wore two 5×5 cm wet gel electrodes just below their left wrist. They were placed on the right side (medial) and spaced about 1 cm apart.

In human-computer interaction, the sensations we investigate have come up in Kruijff et al.’s work on using EMS systems for interaction [27]. While those on-skin sensations were potential confounds in their investigation of muscle activation, our case is different: We would like to focus on the on-skin sensation and avoid muscle activity. Experiential aspects of EMS sensations have recently also been investigated by Knibbe et al. [25]. A study with similar approach, yet with a different focus, is Geng et al.’s work on electrocutaneous stimulation on the forearm [13]. They focused on stimuli with a limited number of pulses and ultimately aim at sensory substitution. A similar goal is pursued by Marcus and Fuglevand with their skin stimulation on the back of the neck [33].

Design

The study was a within-subjects design with the stimulus parameters (frequency, amplitude, and pulse width) as independent variables. We split the study into two phases: An initial qualitative phase with short stimuli and a second phase where participants received longer stimuli. Within each phase, stimulus choice was randomized.

Participants

We recruited 12 participants (2 female, age 22–43, M=29, SD=6.8) from around our institution (whose ethics review process we complied with). Three of the participants had limited experience with electrostimulation devices (“once/a few times”). None of the participants had dermatitis or other skin conditions. As a safety precaution, we also only included participants without any cardiovascular conditions. We obtained participants’ informed consent and let them know that they could withdraw from the study at any time without any repercussions. Participants were given a non-monetary remuneration for participating in the study.

Apparatus

During itch feedback evaluation, participants used our prototype device while seated in front of a computer running the experimental software. Two 5×5 cm self-adhesive wet gel electrodes were attached to the hairy skin of the posterior forearm, just below the left wrist (as shown in Figure 5). We placed the electrodes on the inwards-facing side and about 1 cm apart. For input, participants used a mouse with their right hand.

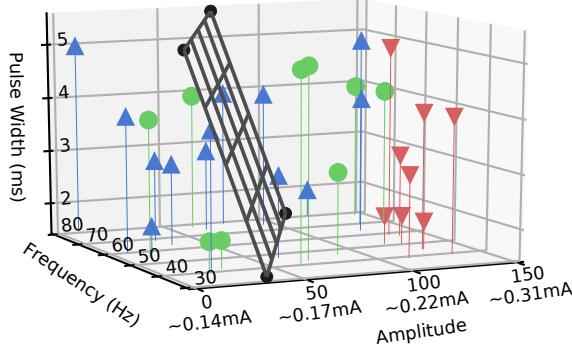


Figure 6. During calibration (shown here for Participant 7), we present several short stimuli to participants. They respond as to whether there was strong movement (red triangle down), slight movement (green circle), or no movement (blue triangle up). We fit a plane to those data to filter out most settings that result in movement. In this example, all parameters to the right of the plane are excluded.

Procedure

After participants provided informed consent, they sat in front of the apparatus and we attached the electrodes. We then performed a **calibration** procedure to determine suitable feedback parameters. Because of individual differences in skin resistance we cannot use the same parameters across all participants: What might be a weak signal for one participant could be a too strong for another one. For the calibration, we asked participants to rate thirty stimuli randomly chosen from the full parameter space (30–80 Hz frequency, 2–5 ms pulse width, and 0–150 steps of the amplitude). Stimuli were only played back for 400 ms to ensure that even if one stimulus was slightly stronger, the discomfort for participants is minimal. For each stimulus, participants then responded whether there was (1) no movement, (2) slight movement, or (3) strong movement in their wrist/hand.

We encoded their responses numerically (0 for no, 1 for slight, and 2 for strong movement intensity) and saved them together with each stimulus' parameters. After all calibration samples had been collected, we used this data to find a plane in the parameter space that separates the range of parameters that resulted in movement from those that do not. This is formulated as a least squares optimization problem where we solve for a plane through a response value of 0.5 (i.e., halfway between no movement and slight movement). We computed this plane via the Levenberg-Marquardt algorithm and saved the resulting weights. Subsequently, we restricted parameter selection to only the part of the parameter space to the left of that plane (see Figure 6 for an example). After successful calibration, at most a few muscle-actuating stimuli were presented to participants.

Prickling	Gentle	Pulling	Vibrating	Pulsating	Itching
Irritating	Strong	Stinging	Soothing	Twitching	Hurting
Localized	Diffuse	Calming	Forceful	Energizing	Jabbing
Squeezing	Faint	Tickling			

Table 1. Terms used by participants to describe the sensations they had in the first study phase. They could pick any number or none of them.

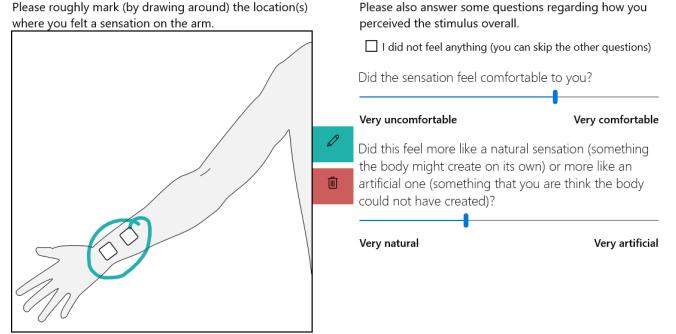


Figure 7. Interfaced used by participants to provide comfort and naturalness ratings during the study's second phase. We also asked them to sketch onto the illustrated arm where they felt the preceding stimulus.

Once calibrated, participants moved on to the **first phase** of the study. In this phase, participants were presented 40 randomly selected stimuli (limited to the calibrated parameter space) for 4 s per stimulus. After each stimulus, we asked them to provide a qualitative assessment of what it felt like. Instead of free-form answers, we asked participants to rate the experience using a provided set of 21 terms. We use the terms on tactile experiences identified by Obrist et al. [41] as a starting point and adapt those to sensations specific to the skin (see Table 1 for a list of all the available terms). We randomized the layout of terms for each trial to avoid ordering effects. Participants were instructed to chose any number of terms that they felt relevant to the experienced stimulus. If they did not feel anything, they could also move on without selecting any term.

So far, in the first phase and during the calibration, we did not ask participants specifically about itching, but hid this aspect within a set of other descriptors. In the **second phase** of the study, we change this and explicitly ask participants about the itching experience. We again sample from the constrained parameter space for a further 10 trials. However, if participants provided an *itching* rating for a stimulus during the first phase, we randomly reuse up to five of those stimuli in the second phase. During a stimulus, a dialog popped up every four seconds asking the participant for ratings of how *itchy* and how *pulsating* the current sensation was. They did so via two continuous visual analogue scales. This delay was intended to allow collection of several ratings per trial, but to provide some time between ratings for participants to just experience the sensations. Stimuli in this phase were presented for at least 20 s or till the last dialog was closed.

At the end of each trial in the second phase, we asked participants for additional ratings (see Figure 7). Apart from rating the level of comfort and how natural they felt the stimulus was (again on visual analogue scales), this also included a task to gather location information. Given an illustration of the arm and the two electrodes, participants marked the area where they felt a sensation during the stimulus.

Overall the study took about 30 minutes. At the end, participants filled out a questionnaire where we gathered additional feedback and overall subjective ratings.



Figure 8. During the calibration phase, participants rated resulting movement intensity for 30 randomly chosen stimuli. We use this data to determine a per-participant thresholding function to eliminate parameters that result in movement in subsequent trials. Shown here are all participant responses and how they relate to the derived calibration.

Results

Participants experienced a wide range of sensations during our evaluation. We look at results from each of the study phases separately.

Calibration Phase

Figure 8 shows how participants' reactions to the calibration stimuli varied. Where Participant 7 experienced many instances of strong movement, Participant 6 did not experience any. Since what constitutes strong and slight movement is subjective, participants employed different strategies here. Anecdotally, some participants were more “enduring” and gave ratings of slight movement even for stronger stimuli. Others were more sensitive and rated a large share of trials as at least causing slight movement.

Overall, while there were instances of strong movement, the experimenter did not observe visibly strong muscle activations in subsequent trials. Thus, the calibration phase successfully limited the range to one more applicable to electrotactile experiences. This also shows in the participants' responses in the later qualitative rating tasks, which we describe below.

First Study Phase

In the first phase, participants provided 1199 terms in 480 trials, an average of 2.5 terms per trial. This varied between participants and while Participant 7 only provided 45 terms, Participant 10 selected 164. The most common sensation was *vibrating*, which was used 121 times to describe a stimulus. We saw more than double the ratings relating to lower intensity (*gentle*, *faint*) than ratings relating to high intensity (*strong*, *forceful*). This further suggests that our calibration successfully constrained the space. As we told participants that strong stimuli were acceptable the presence of *forceful* stimuli is not surprising. Stimuli where participants actually indicated a *hurting* sensation (even if weak) only made up 2 % of trials.

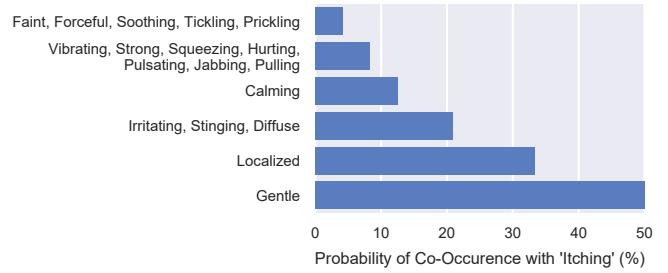


Figure 9. For trials where participants selected *itching* as a descriptor, we here show the other labels co-occurring. Surprisingly, the label *gentle* is used in many of the same trials. However, we also see some co-occurrence of more related terms, such as *stinging*, *irritating*, or *prickling*.

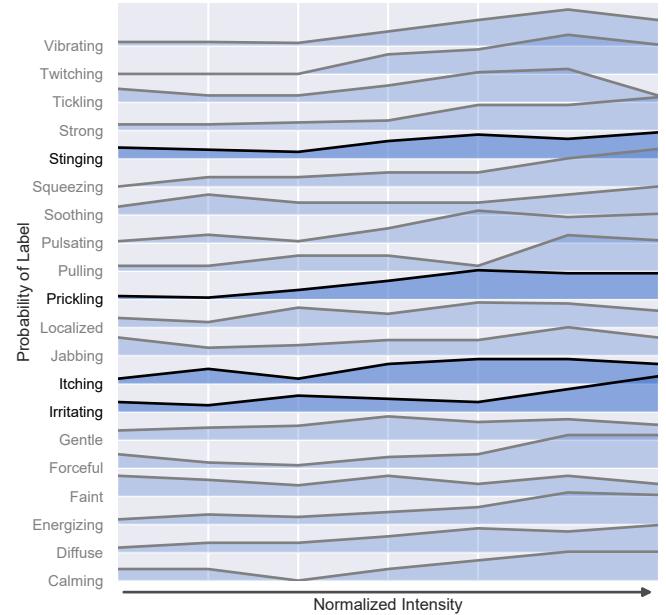


Figure 10. Depending on how intense a stimulus is (relative to the thresholds participants defined during the calibration), different ratings are used. In general, an increase in intensity results in increased levels of sensation (see, e.g., the *strong* label). Highlighted here are sensations more closely relating to *itching*.

In 24 trials participants described a sensation as *itching*. One reason for this low frequency is that we did not constrain the parameters to those generally found to be more prone to *itching*, but tested a larger subset of non-actuating stimuli. But there are also likely differences in what participants view as *itching*. As we did not prime them to look for *itching*, or even mentioned *itching* in any way at this point, they might use different terms to describe an *itching*-like experience.

To develop a better understanding for what terms correlate with *itching* we look at the trials where the term *itching* was used together with other terms. As shown in Figure 9, *itching* has connections to *stinging*, *irritating*, as well as to *prickling*. However, surprisingly, the *itching* descriptor also appears together with terms such as *gentle* and *calming*. It seems that *itching* is not necessarily strong and hurting (other terms it correlates with), but can also be a more subtle sensation that is less overpowering.

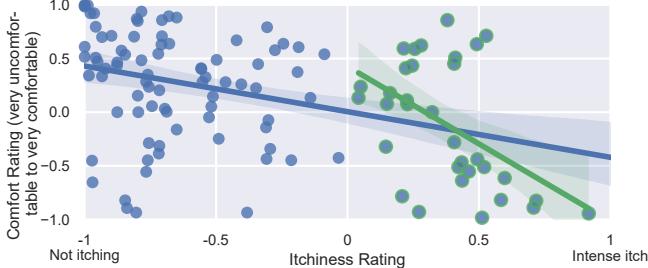


Figure 11. Shown here is the relationship between itchiness and comfort ratings. Overall, we see a slight trend for increased discomfort as itchiness increases. However, this includes many trials where there was no itching felt in general. If we restrict our view of this relationship to the trials where above neutral levels of itching were perceived (shown in green), this relation of itching to discomfort becomes much clearer.

We can relate the qualitative experiences to the intensity of the stimulus that evoke them. Intensity is relative to each participant's calibration. The fitted plane gives the threshold between stimuli that are actuating and those that are not. The further one moves to the left of that plane the weaker stimuli get. We discretize this distance for all participants, which sorts qualitative ratings into per-participant intensity bins. These can then be combined over all participants to provide a normalized view of where which sensations occur in the parameter space.

Figure 10 shows which sensations occur where along the intensity spectrum. We can see a general trend for more sensation the higher the signal intensity, including for the highlighted itching-related sensations. But this figure also shows the intensity alone is not a good predictor of what a user will perceive. In the same intensity bin sensations like *vibrating*, *squeezing*, and *itching* coincide, yet were never used together in any trial.

Second Study Phase

Where we collected general sensation ratings in the first phase, we asked participants directly for itchiness ratings in the second phase. This phase was designed to collect multiple ratings over the stimulus duration, but we found that it took most participants too long to provide ratings. We thus do not report on changes in itch perception over longer stimulus durations, but focus on the overall ratings and, in particular, how they relate to participants' comfort levels.

Figure 11 shows all ratings of itchiness and comfort together, indicating that increased itching leads to discomfort. This includes many trials where no itching was felt by the participants. If we only look at the itchiness to comfort relationship for trials where some itching was perceived, this relationship becomes clearer. In fact, while slight itch can be comfortable, we recorded no trials with intense itch that were also rated as comfortable.

In this phase we reused up to five stimuli from the first phase if participants rated them as itching. It is thus possible that these participants had a higher likelihood for actual itching experiences in this phase. Another possibility is that some participants describe sensations as itching, where others might resort to different descriptors. We investigated the influence of how many stimuli were reused on the average itching ratings in the second phase.

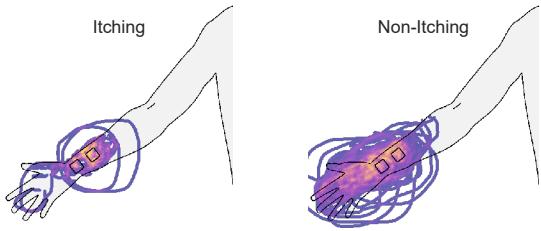


Figure 12. Based on participants' markings of where they felt a sensation, we here compare trials where they felt itching (itching rating at least 10 % above the neutral starting point of the itching scale) and where they did not. The number of trials composing the left view is only 27 % of the total. However, the data still suggests that itching is slightly more localized than the other sensations we evoked.

Linear regression showed a significant influence ($p < 0.01$) of percentage of reuse on the average itchiness ($r^2 = 0.6$). In fact, an independent samples t-test showed significantly larger itchiness ratings for repeated stimuli than for newly drawn ones ($p < 0.001$). This is not surprising as we randomly sample the parameter space and do not bias this towards areas of itching. Yet, this also shows that there is consistency in participants' ratings as they also perceived itchiness in repeated presentations. Thus, stimulus parameters can likely be calibrated per-participant to evoke specific sensations, once a suitable setting has been determined.

As described above, we also asked participants during this phase to mark the area where they perceived a sensation. For some participants the sensations were much more localized than for others. Where Participant 1 pointed out small areas around the electrodes, others, such as Participant 12, described sensations all the way down their fingers. The fact that this kind of sensation can be felt beyond the immediate stimulation area could potentially enable designs not feasible with other means of feedback. For example, this hints at the fact that there might be some flexibility as to the placement of the stimulator and could bode well for integration into wearables.

Instead of the overall stimulation area, we can look more closely at those trials where participants felt an itching sensation. As shown in Figure 12, itching sensations appear to cluster more closely around the electrodes than non-itching sensations. Interestingly, there also seems to be a slight bias towards the proximal electrode. Where non-itching sensations often would extend all the way to the finger tips, itching sensations were more localized.

Itching Parameters

If we average over all participants, then the ideal signal for itching is a 60 Hz wave with 3.8 ms pulse width and an amplitude of about 0.2 mA. However, there is much variation between participants. We can limit this by only considering the participants who experienced at least five trials with itching. This yields similar averages, but also shows that while the variance of the frequency and pulse width parameters decreases, variance for the amplitude remains higher. The signal strength thus is likely the parameter varying the most between participants. What amplitude is required for a consistent sensation is also influenced by electrode placement, which could also be a factor in the differences we see in our results.

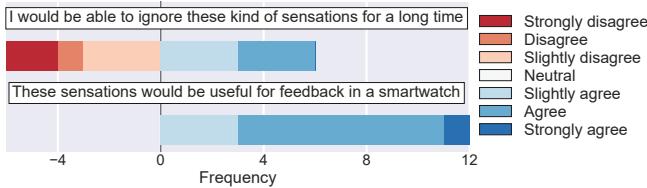


Figure 13. Participants' responses to the exit questionnaire.

Subjective Experiences

Figure 13 shows subjective ratings from our participants. Asked how easy to ignore they thought the kind of feedback they experienced was, participants gave mixed responses. This might be due to the wide range of sensations, where some are gentle and soothing and thus more easily ignorable, while others are more intense and less easy to ignore. However, the average comfort rating (per the second phase trials) and the participants' perceived ability to ignore the feedback were not correlated: Spearman's rank correlation coefficient $r_s = 0.0, p = 0.99$. The level of itching also did not correlate: Spearman's rank correlation coefficient $r_s = -0.1, p = 0.67$. Hence, there is no clear relationship between the final experiences in the second phase and participants response.

The majority of the participants responded that they mostly perceived on-skin sensations and not finger actuation. This again confirms that our calibration worked and we were able to limit actuating sensations.

All participants saw potential in integrating this kind of feedback into future smartwatches. One participant remarked that this feedback: “could be cool if it could tell you through a smartwatch if it was a message, special call, etc.” (P6)

Many participants also remarked on what the sensations felt like to them. Sensations could be “either kind of stingy and ‘working me up’ (causing to move), or totally relaxing and causing me to lean back and relax” (P2). This range was also described as: “the calm, almost not sensable sensation were soothing and kind of dreamy. The others were not irritating, but most of the time uncomfortable — though some were just there” (P8). Sensations could be “a general feeling of something interfering with the hairs on your arm” (P10). But it could also be that “most of the sensations felt quite unnatural” (P11). One participant noted that “most comfortable was the ones pulsating instead of vibrating” (P11).

Some participants likened the sensations to specific previous experiences. For example, “one type was similar to when my arm is ‘sleeping’” (P12). more unconventionally, “once after a hash cookie I woke up as being hit by electricity; some stronger vibes remind me of that” (P5). Another participant remarked that “it feels like being stung by a lot of small needles, and you feel the urge to scratch” (P10).

There were also some comments relating to the location of the sensations. For example, the sensation could be “very pulsating in/on specific spots on my arm” (P6). But it was also “completely focused on a small area (2 fingers + wrist)” (P9). One participant remarked on an effect after the signal was already off, where “the sensation lingers afterwards a little bit. I can feel a slight irritation in my ring finger” (P8).

Discussion

Our first evaluation has shown that we have found parameters that caused itching sensations for the participants. However, the sensation of itching is mixed with a range of other sensations. Similar to itching, some of these other sensations were also uncomfortable, but the majority was more pleasant. In other cases, participants received gentle, relaxing, and calming sensations. This demonstrates that this kind of feedback holds the potential for not just “uncomfortable interactions” [2], but could also be used for the opposite.

If we relate this back to the two questions we set out to investigate then we can see that the answer to **Q1** is complex. There is an overall pattern that increased intensity results in more pronounced sensations. Yet, this does not guarantee itching and it is only in the right combination of all three dimensions that this kind of sensation is evoked.

With regards to **Q2**, we gained several insights into the properties of itch stimuli. As participants remarked in the final questionnaire, the itching caused them to move and perceive “the urge to scratch”. A large difference was seen in comparison to the more relaxing sensations, where one participant went so far as to describe the sensation as “dreamy”. The data from the stimulus localization task also suggests that itching might be more localized than other sensations.

COMPARING ITCHING AND VIBRATION FEEDBACK

In the first study we investigated which electrotactile feedback signals can evoke itch. With this second study we focus on the notification properties of itching. The responses of the first study's participants underlined the potential of this application. Furthermore, previous work suggests that itching would have activating and demanding properties when used for notifications. We confirm this here in a comparison of itching and vibrotactile feedback in a smartwatch. Furthermore, this second study allows us to directly test the consistency of itch stimuli, by focusing on stimuli we found likely to itch instead of randomly sampling the space.

Design

The study is a within-subjects design with feedback type (itching or vibration) as independent variable.

Participants

We recruited 14 participants (8 female, age 20–32, M=25.1, SD=3.4) via a mailing list. 5 of these participants already took part in our first study (about half a year earlier). The same precautions and process as in the first study were used.

Apparatus

We use the same stimulator as in the previous study. The vibrotactile feedback is generated by an Apple Watch (see Figure 14). We affixed itch stimulation electrodes to the watch strap. We deem this the likeliest location for future integration into smartwatches. Instead of wet electrodes we use copper tape as electrode material, as it conforms to the watch strap's shape. For three of our participants the electrodes made insufficient contact with their wrist. Those participants instead wore wet electrodes in the same location. We envision that electrode traces and pads would be directly integrated into future straps (e.g., via a conductive rubber material).



Figure 14. To compare itching with vibrotactile feedback we augment an Apple Watch with electrodes on the watch strap.

Procedure

This study again started with a calibration phase. We asked participants to increase the intensity until they could clearly perceive a sensation. The initial frequency and pulse width parameters were set to itching parameters determined in our first study. Participants could also adjust the signal frequency to maximize the sensation of itching. Afterwards, during the study, itch stimuli lasted 3 s when played back.

In the first phase, participants rated itch and vibrotactile stimuli. Leaning on the IRC framework [35], we asked participants to rate how (1) interruptive they perceived a stimulus, and (2) how much they felt a stimulus prompted them to act. We did not consider the third dimension, comprehension, in this phase. For itch stimuli, we also asked participants to rate the level of itching. We used four different stimuli for this phase: the calibrated itching, modified itching (10 % higher amplitude and 10 % lower frequency), and two vibrotactile cues (the “notification” and “retry” types on the Apple Watch). Stimuli order was randomized and each stimulus repeated 5 times.

We were also interested in preferences for specific kinds of notifications. In a second phase we hence asked participants to indicate preferences (by ordering) of stimuli for a set of notification scenarios (see Figure 16). We derive these scenarios from smartwatch usage patterns, reported in the literature [5, 18, 52]. Participants could play back each stimulus as often as they desired in this phase. In addition to ranking the stimuli, we also asked participants to verbalize their reasons for this ranking. We finished the study with a short interview.

Results

Because three participants used a different electrode setup than the others, we first confirmed there was no systematic difference between these two groups. We ran a Mann-Whitney U test to evaluate differences in the groups’ itch ratings. We found no significant effect of electrode type; $U = 8, p = 0.4$.

As participants reused the same itching stimuli throughout this study, we can examine how consistently itching sensations were generated. The mean and median itch ratings were 3.9 and 4.0 respectively on a 0–5 Likert scale and about 90 % of the trials resulted in a clear itch sensation. All but two participants reported consistent itching (with some variation, e.g., due to shifting strap placement)—the mean interquartile range for all participants was only one score point. Those two participants still felt some itching, but were removed from further analysis. Overall, the results indicate we were able to consistently and reliably induce itch sensations.

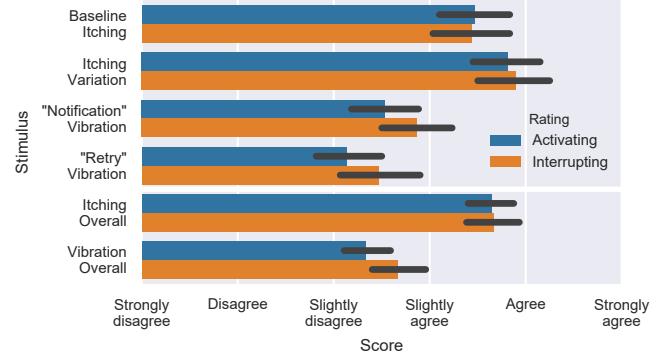


Figure 15. Participants rated itching stimuli as more interrupting as well as more activating (prompting a response) than vibration stimuli. Error bars show bootstrapped 95 % confidence intervals.

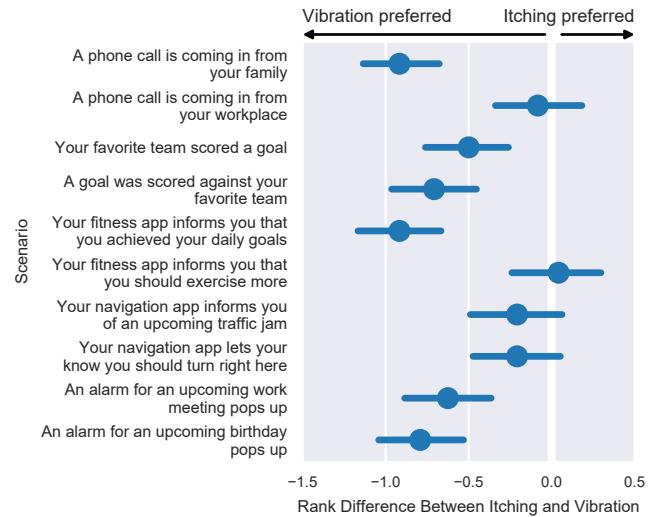


Figure 16. For ten notification scenarios, participants ranked the four feedback options. Here, we show the differences in ranking between the vibration and itching stimuli. Vibration is overall slightly preferred, but itching provides an advantage for the less pleasant scenario options. Error bars show bootstrapped 95 % confidence intervals.

We find that itching stimuli were rated as more interrupting as well as more activating than vibration stimuli (see Figure 15). Friedman tests showed a significant effect of stimulus on both scores; $\chi^2(3) = \{12.4, 17.9\}, p < 0.01$. As the differences between the two variations of each feedback type were small, we aggregated these in further analyses. Using Wilcoxon tests to compare the overall itching and vibration ratings, we correspondingly also found significant differences between them for both interrupting and activating ratings; $p < 0.001$.

As shown in Figure 16, participants preferred vibration feedback for most scenarios. However, depending on the given context, feedback preferences differed. While vibration was more strongly preferred for family messaging, this weakens in a work context. Similarly, more people saw a use for itching when missing fitness goals than when achieving them. This suggests more somber and negative contexts could be a good fit for itch feedback.

Participants noted multiple differences between itching and vibration. Several participants described itching as “more intense” (P4), “much stronger” (P1), “hard to ignore” (P6, P13), and “urgent” (P5). Similarly, vibration was perceived as “easier to ignore” (P11), “easy to [overlook]” (P7), and “more familiar” (P3). Participant 12 provided a representative summary by stating that the itching was “uncomfortable” and he was “forced to react,” which led him to prefer vibration for postponable notifications and itching for urgent ones.

Participants also described their ranking strategy. They chose vibration for “good/positive” (P1), “less important” (P11), “comfortable” (P9), or “more relaxed” (P2) situations. They chose itching for “important” (P1, P5, P9, P11, P13, P14) and “urgent” (P12) situations. Yet, two participants picked vibration feedback for “important” situations (P8, P10). Vibration was also preferred when participants feared distraction from itching when driving (P6, P7, P9).

Two participants remarked on the connection between “punishment” and itch feedback. Furthermore, one participant pointed out that he felt itching had its “source of origin [...] inside the arm”, while “vibration [acted] from outside” (P8). One participant (P13) also remarked on the beneficial properties of silent itch feedback when in a movie theater.

Discussion

The results demonstrate that itching and vibration feedback differ in fundamental ways. Itching is significantly more interrupting and activating than vibration feedback. Thus, not only do users notice it, they are strongly prompted to *act* on this feedback. This is in line with the general properties of itch, as described earlier. But because of this difference, itching also is the less appropriate choice in some scenarios. Participants were more likely to prefer vibration feedback for notifications related to family, achievements, or hobbies. Yet, in more pressing or somber scenarios, itching can be a suitable alternative.

Our participants’ interview responses further hint at those differences. Itch was associated with more urgent and important notifications, but vibration feedback was overall more pleasant. As most notifications are likely not urgent or important, this led to the overall preference for vibration feedback. However, our participants’ responses show that itching has the potential to supplement vibration feedback for more urgent or important notifications.

Finally, the comment by P8 on the source of itching and vibration points to the fact that itching is a sensation that acts *within* the body. Vibration on the other hand is seen as acting from the outside. This raises further questions on what this difference means for what is seen as more *natural*.

APPLICATIONS

In our investigation of itch feedback, we have focused on the use case of notifications. However, we see several other applications where itch feedback could be valuable. One example is Metha et al.’s envisioned *privacy itch and scratch*, where a user’s arm starts to itch as a “privacy breach” occurs [37].

We see particular promise for itching in nudging scenarios, where users desire to break bad habits. Itching could also be used to create discomfort to get users to shift their body, for example, to change seating posture. Itching could also be added to VR applications to provide more realistic feedback when touching, for example, virtual poison ivy.

CONCLUSION

In this paper we have investigated itching as a form of feedback for interactive devices. Itching holds several properties that make it an attractive choice for integration into systems. Not only does it grab our attention, it also pushes us towards action. Just because itching is uncomfortable should not preclude its use in interactive systems. In fact, that very discomfort is what reinforces the activating properties itching holds.

Starting from a description of itching, we have described several ways itching sensations can be created. From these, electrical stimulation is the most suited for use in interactive devices. This connects itching feedback to the large area of work on functional electrical stimulation, such as used for electric muscle stimulation. Inspired by the existing designs for electric stimulators, we have presented a small and mobile-ready prototype for creating a range of electrotactile stimuli. With our device and studies we have focused only on the wrist and other feedback locations need to be explored by future work.

In our first study, we have investigated what parameters lead to itching and how itching interacts with other sensations. All participants experienced itching, yet we found that signal parameters are in a complex interplay and per-participant calibration is necessary.

In our second study we directly compared itching against vibration. We also confirmed that itching stimuli can be calibrated for and then consistently applied. We found that compared to vibration feedback, itching is more interrupting and activating. Our participants’ preference patterns also showed that vibration and itching feedback have distinct areas where they are seen as advantageous. Itching feedback here showed potential for complementing vibration feedback when more intense activation is needed or in less casual contexts.

Our interviews point to several aspects of itching that warrant further investigation. Itching was seen as occurring *within* the body and several participants remarked the need to scratch the itch site. Both these properties are unique to itch feedback and hint that itching might be a potentially more natural way to provide notifications. However, additional studies are required to investigate the combination of itch feedback with scratch input (detection of which previous work has shown [40, 29]). Furthermore, it is presently unclear whether any useful properties can emerge from the differences between feedback perceived *on the surface of* and *within* the body.

ACKNOWLEDGEMENTS

We would like to thank Tim Dünte and Jan Oechsle for their help with building the electrotactile stimulator. This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation program (grant agreement 648785).

REFERENCES

1. Amay J. Bandodkar, Wenzhao Jia, Ceren Yardimci, Xuan Wang, Julian Ramirez, and Joseph Wang. 2015. Tattoo-Based Noninvasive Glucose Monitoring: A Proof-of-Concept Study. *Analytical Chemistry* 87, 1 (2015), 394–398. DOI: <http://dx.doi.org/10.1021/ac504300n>
2. Steve Benford, Chris Greenhalgh, Gabriella Giannachi, Brendan Walker, Joe Marshall, and Tom Rodden. 2012. Uncomfortable Interactions. In *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI '12*. ACM Press, New York, New York, USA, 2005–2014. DOI: <http://dx.doi.org/10.1145/2207676.2208347>
3. G.A. bin Saif, A.D.P. Papouli, L. Banari, F. McGlone, S.G. Kwatra, Y-H. Chan, and G. Yosipovitch. 2012. The pleasurability of scratching an itch: a psychophysical and topographical assessment. *British Journal of Dermatology* 166, 5 (may 2012), 981–985. DOI: <http://dx.doi.org/10.1111/j.1365-2133.2012.10826.x>
4. G. H. Bishop. 1943. Responses to Electrical Stimulation of Single Sensor Units of Skin. *Journal of Neurophysiology* 6, 5 (1943), 361–382.
5. Marta E. Cecchinato, Anna L. Cox, and Jon Bird. 2015. Smartwatches: the Good, the Bad and the Ugly?. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA '15*. ACM Press, New York, New York, USA, 2133–2138. DOI: <http://dx.doi.org/10.1145/2702613.2732837>
6. S. R. Corrie, J. W. Coffey, J. Islam, K. A. Markey, and M. A. F. Kendall. 2015. Blood, sweat, and tears: developing clinically relevant protein biosensors for integrated body fluid analysis. *The Analyst* 140, 13 (2015), 4350–4364. DOI: <http://dx.doi.org/10.1039/C5AN00464K>
7. J. A. De Lima and A. S. Cordeiro. 2002. A Low-Cost Neurostimulator with Accurate Pulsed-Current Control. *IEEE Transactions on Biomedical Engineering* 49, 5 (may 2002), 497–500. DOI: <http://dx.doi.org/10.1109/10.995689>
8. Tim Duente, Max Pfeiffer, and Michael Rohs. 2017. Zap++: A 20-Channel Electrical Muscle Stimulation System for Fine-Grained Wearable Force Feedback. In *Proceedings of the 19th International Conference on Human-Computer Interaction with Mobile Devices and Services - MobileHCI '17*. ACM Press, New York, New York, USA, 1:1–1:13. DOI: <http://dx.doi.org/10.1145/3098279.3098546>
9. Christopher Eccleston. 2016. Itch. In *Embodied: The psychology of physical sensation* (1st ed.). Oxford University Press, Oxford, UK, 45–66. DOI: <http://dx.doi.org/10.1093/acprof:oso/9780198727903.003.0008>
10. A. E. Edwards, W. V. Shellow, E. T. Wright, and T. F. Dignam. 1976. Pruritic Skin Diseases, Psychological Stress, and the Itch Sensation: A Reliable Method for the Induction of Experimental Pruritus. *Arch Dermatol* 112, 3 (1976), 339–343. DOI: <http://dx.doi.org/10.1001/archderm.1976.01630270019004>
11. Marta Franceschi, Lucia Seminara, Strahinja Dosen, Matija Strbac, Maurizio Valle, and Dario Farina. 2017. A System for Electrotactile Feedback Using Electronic Skin and Flexible Matrix Electrodes: Experimental Evaluation. *IEEE Transactions on Haptics* 10, 2 (apr 2017), 162–172. DOI: <http://dx.doi.org/10.1109/TOH.2016.2618377>
12. Miyuki Fukuoka, Yoshiaki Miyachi, and Akihiko Ikoma. 2013. Mechanically evoked itch in humans. *Pain* 154, 6 (2013), 897–904. DOI: <http://dx.doi.org/10.1016/j.pain.2013.02.021>
13. Bo Geng, Ken Yoshida, Laura Petrini, and Winnie Jensen. 2012. Evaluation of sensation evoked by electrocutaneous stimulation on forearm in nondisabled subjects. *The Journal of Rehabilitation Research and Development* 49, 2 (2012), 297–308. DOI: <http://dx.doi.org/10.1682/JRRD.2010.09.0187>
14. Richard J. Hall. 2008. If it itches, scratch! *Australasian Journal of Philosophy* 86, 4 (dec 2008), 525–535. DOI: <http://dx.doi.org/10.1080/00048400802346813>
15. Liang Han and Xinzhong Dong. 2014. Itch Mechanisms and Circuits. *Annual Review of Biophysics* 43, 1 (may 2014), 331–355. DOI: <http://dx.doi.org/10.1146/annurev-biophys-051013-022826>
16. Mark R. Holcomb, Jack M. Devine, Rene Harder, and Veniamin Y. Sidorov. 2012. Continuous-waveform constant-current isolated physiological stimulator. *Review of Scientific Instruments* 83, 4 (apr 2012), 044303. DOI: <http://dx.doi.org/10.1063/1.3700977>
17. Akihiko Ikoma, Hermann Handwerker, Yoshiki Miyachi, and Martin Schmelz. 2005. Electrically evoked itch in humans. *Pain* 113, 1-2 (2005), 148–154. DOI: <http://dx.doi.org/10.1016/j.pain.2004.10.003>
18. Hayeon Jeong, HeePyung Kim, Rihun Kim, Uichin Lee, and Yong Jeong. 2017. Smartwatch Wearing Behavior Analysis: A Longitudinal Study. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 1, 3 (sep 2017), 1–31. DOI: <http://dx.doi.org/10.1145/3131892>
19. K.A. Kaczmarek, K.M. Kramer, J.G. Webster, and R.G. Radwin. 1991a. A 16-Channel 8-Parameter Waveform Electrotactile Stimulation System. *IEEE Transactions on Biomedical Engineering* 38, 10 (oct 1991), 933–943. DOI: <http://dx.doi.org/10.1109/10.88439>
20. K.A. Kaczmarek, J.G. Webster, P. Bach-y Rita, and W.J. Tompkins. 1991b. Electrotactile and Vibrotactile Displays for Sensory Substitution Systems. *IEEE Transactions on Biomedical Engineering* 38, 1 (1991), 1–16. DOI: <http://dx.doi.org/10.1109/10.68204>

21. H. Kajimoto, N. Kawakami, S. Tachi, and M. Inami. 2004. SmartTouch: Electric Skin to Touch the Untouchable. *IEEE Computer Graphics and Applications* 24, 1 (jan 2004), 36–43. DOI: <http://dx.doi.org/10.1109/MCG.2004.1255807>
22. Hsin-Liu (Cindy) Kao, Christian Holz, Asta Roseway, Andres Calvo, and Chris Schmandt. 2016. DuoSkin: Rapidly Prototyping On-Skin User Interfaces Using Skin-Friendly Materials. In *Proceedings of the 2016 ACM International Symposium on Wearable Computers - ISWC '16*. ACM Press, New York, New York, USA, 16–23. DOI: <http://dx.doi.org/10.1145/2971763.2971777>
23. Thierry Keller, Marc Lawrence, Andreas Kuhn, and Manfred Morari. 2006. New Multi-Channel Transcutaneous Electrical Stimulation Technology for Rehabilitation. In *2006 International Conference of the IEEE Engineering in Medicine and Biology Society*. IEEE, 194–197. DOI: <http://dx.doi.org/10.1109/IEMBS.2006.259399>
24. Dae-Hyeong Kim, Nanshu Lu, Rui Ma, Yun-Soung Kim, Rak-Hwan Kim, Shuodao Wang, Jian Wu, Sang Min Won, Hu Tao, Ahmad Islam, Ki Jun Yu, Tae-il Kim, Raeed Chowdhury, Ming Ying, Lizhi Xu, Ming Li, Hyun-Joong Chung, Hohyun Keum, Martin McCormick, Ping Liu, Yong-Wei Zhang, Fiorenzo G. Omenetto, Yonggang Huang, Todd Coleman, and John A. Rogers. 2011. Epidermal Electronics. *Science* 333, 6044 (2011), 838–843. DOI: <http://dx.doi.org/10.1126/science.1206157>
25. Jarrod Knibbe, Adrian Alsmith, and Kasper Hornbæk. 2018. Experiencing Electrical Muscle Stimulation. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 2, 3 (2018).
26. Michinari Kono, Takumi Takahashi, Hiromi Nakamura, Takashi Miyaki, and Jun Rekimoto. 2018. Design Guideline for Developing Safe Systems that Apply Electricity to the Human Body. *ACM Transactions on Computer-Human Interaction* 25, 3 (jun 2018), 1–36. DOI: <http://dx.doi.org/10.1145/3184743>
27. Ernst Kruijff, Dieter Schmalstieg, and Steffi Beckhaus. 2006. Using Neuromuscular Electrical Stimulation for Pseudo-Haptic Feedback. In *Proceedings of the ACM symposium on Virtual reality software and technology - VRST '06*. ACM Press, New York, New York, USA, 316–319. DOI: <http://dx.doi.org/10.1145/1180495.1180558>
28. Gierad Laput, Robert Xiao, Xiang 'Anthony' Chen, Scott E. Hudson, and Chris Harrison. 2014. Skin Buttons: Cheap, Small, Low-Powered and Clickable Fixed-Icon Laser Projectors. In *Proceedings of the 27th annual ACM symposium on User interface software and technology - UIST '14*. ACM Press, New York, New York, USA, 389–394. DOI: <http://dx.doi.org/10.1145/2642918.2647356>
29. Jongin Lee, Daeki Cho, Junhong Kim, Eunji Im, JinYeong Bak, Kyung ho Lee, Kwan Hong Lee, and John Kim. 2017. Itchector: A Wearable-based Mobile System for Managing Itching Conditions. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems - CHI '17*. ACM Press, New York, New York, USA, 893–905. DOI: <http://dx.doi.org/10.1145/3025453.3025569>
30. D. M. Lloyd, E. Hall, S. Hall, and F. P. McGlone. 2013. Can itch-related visual stimuli alone provoke a scratch response in healthy individuals? *British Journal of Dermatology* 168, 1 (2013), 106–111. DOI: <http://dx.doi.org/10.1111/bjd.12132>
31. Joanne Lo, Doris Jung Lin Lee, Nathan Wong, David Bui, and Eric Paulos. 2016. Skintillates: Designing and Creating Epidermal Interactions. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems - DIS '16*. ACM Press, New York, New York, USA, 853–864. DOI: <http://dx.doi.org/10.1145/2901790.2901885>
32. Alessio Malizia and Andrea Bellucci. 2012. The Artificiality of Natural User Interfaces. *Commun. ACM* 55, 3 (mar 2012), 36–38. DOI: <http://dx.doi.org/10.1145/2093548.2093563>
33. Patrick L. Marcus and Andrew J. Fuglevand. 2009. Perception of electrical and mechanical stimulation of the skin: implications for electrotactile feedback. *Journal of Neural Engineering* 6, 6 (2009), 066008:1–066008:12. DOI: <http://dx.doi.org/10.1088/1741-2560/6/6/066008>
34. Aizan Masdar, B. S. K. K. Ibrahim, and M. Mahadi Abdul Jamil. 2012. Development of Wireless-Based Low-Cost Current Controlled Stimulator for Patients with Spinal Cord Injuries. In *2012 IEEE-EMBS Conference on Biomedical Engineering and Sciences*. IEEE, 493–498. DOI: <http://dx.doi.org/10.1109/IECBES.2012.6498175>
35. D. Scott McCrickard, C. M. Chewar, Jacob P. Somervell, and Ali Ndwalana. 2003. A Model for Notification Systems Evaluation—Assessing User Goals for Multitasking Activity. *ACM Transactions on Computer-Human Interaction* 10, 4 (dec 2003), 312–338. DOI: <http://dx.doi.org/10.1145/966930.966933>
36. Michael John McNulty and Padraig Fogarty. 2006. Design of a highly efficient circuit for electrical muscle stimulation. *IEEE 2006 Biomedical Circuits and Systems Conference Healthcare Technology, BioCAS 2006* (2006), 202–205. DOI: <http://dx.doi.org/10.1109/BIOCAS.2006.4600343>
37. Vikram Mehta, Arosha K. Bandara, Blaine A. Price, and Bashar Nuseibeh. 2016. Privacy Itch and Scratch: On Body Privacy Warnings and Controls. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA '16*. ACM Press, New York, New York, USA, 2417–2424. DOI: <http://dx.doi.org/10.1145/2851581.2892475>

38. Adiyan Mujibiyia, Xiang Cao, Desney S. Tan, Dan Morris, Shwetak N. Patel, and Jun Rekimoto. 2013. The Sound of Touch: On-Body Touch and Gesture Sensing Based on Transdermal Ultrasound Propagation. In *Proceedings of the 2013 ACM international conference on Interactive tabletops and surfaces - ITS '13*. ACM Press, New York, New York, USA, 189–198. DOI: <http://dx.doi.org/10.1145/2512349.2512821>
39. R. H. Nathan. 1979. Functional electrical stimulation of the upper limb: charting the forearm surface. *Medical & Biological Engineering & Computing* 17, 6 (nov 1979), 729–736. DOI: <http://dx.doi.org/10.1007/BF02441554>
40. Yuichi Noro, Youichi Omoto, Koji Umeda, Futa Tanaka, Yousuke Shiratsuka, Tomomi Yamada, Kenichi Isoda, Kimiko Matsubara, Keiichi Yamanaka, Esteban C. Gabazza, Masakatsu Nishikawa, and Hitoshi Mizutani. 2014. Novel acoustic evaluation system for scratching behavior in itching dermatitis: Rapid and accurate analysis for nocturnal scratching of atopic dermatitis patients. *Journal of Dermatology* 41, 3 (2014), 233–238. DOI: <http://dx.doi.org/10.1111/1346-8138.12405>
41. Marianna Obrist, Sue Ann Seah, and Sriram Subramanian. 2013. Talking about Tactile Experiences. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '13*. ACM Press, New York, New York, USA, 1659–1668. DOI: <http://dx.doi.org/10.1145/2470654.2466220>
42. Masa Ogata, Yuta Sugiura, Yasutoshi Makino, Masahiko Inami, and Michita Imai. 2013. SenSkin: Adapting Skin as a Soft Interface. In *Proceedings of the 26th annual ACM symposium on User interface software and technology - UIST '13*. ACM Press, New York, New York, USA, 539–544. DOI: <http://dx.doi.org/10.1145/2501988.2502039>
43. Maki Ozawa, Kenichiro Tsuchiyama, Rumiko Gomi, Fumio Kurosaki, Yuji Kawamoto, and Setsuya Aiba. 2006. Neuroselective transcutaneous electric stimulation reveals body area-specific differences in itch perception. *Journal of the American Academy of Dermatology* 55, 6 (2006), 996–1002. DOI: <http://dx.doi.org/10.1016/j.jaad.2006.08.032>
44. A.D.P. Papoiu, H. Wang, R.C. Coghill, Y-H. Chan, and G. Yosipovitch. 2011. Contagious itch in humans: a study of visual ‘transmission’ of itch in atopic dermatitis and healthy subjects. *British Journal of Dermatology* 164, 6 (jun 2011), 1299–1303. DOI: <http://dx.doi.org/10.1111/j.1365-2133.2011.10318.x>
45. Henning Pohl, Kasper Hornbæk, and Jarrod Knibbe. 2018. Wanding Through Space: Interactive Calibration for Electric Muscle Stimulation. In *Proceedings of the 9th Augmented Human International Conference on - AH '18*. ACM Press, New York, New York, USA, 19:1–19:5. DOI: <http://dx.doi.org/10.1145/3174910.3174948>
46. Henning Pohl, Justyna Medrek, and Michael Rohs. 2016. ScatterWatch: Subtle Notifications via Indirect Illumination Scattered in the Skin. In *Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services - MobileHCI '16*. ACM Press, New York, New York, USA, 7–16. DOI: <http://dx.doi.org/10.1145/2935334.2935351>
47. C.J. Poletto and C.L. Van Doren. 1999. A High Voltage, Constant Current Stimulator for Electrocutaneous Stimulation Through Small Electrodes. *IEEE Transactions on Biomedical Engineering* 46, 8 (1999), 929–936. DOI: <http://dx.doi.org/10.1109/10.775402>
48. Mark R. Prausnitz. 1996. The effects of electric current applied to skin: A review for transdermal drug delivery. *Advanced Drug Delivery Reviews* 18, 3 (feb 1996), 395–425. DOI: [http://dx.doi.org/10.1016/0169-409X\(95\)00081-H](http://dx.doi.org/10.1016/0169-409X(95)00081-H)
49. Gary B. Rollman. 1974. Electrocutaneous stimulation. In *Conference on cutaneous communication systems and devices*.
50. J. E. Ross, D. F. Lovely, and P. A. Parker. 2000. Design of a PC Controlled Constant Current Stimulator for Evoked Potential Studies. In *Proceedings of the 22nd Annual International Conference of the IEEE Engineering in Medicine and Biology Society (Cat. No.00CH37143)*, Vol. 4. IEEE, 2594–2596. DOI: <http://dx.doi.org/10.1109/IEMBS.2000.901388>
51. Debabrata Sarddar, Madhurendra Kumar, and Suman Kumar Sikdar. 2012. Functional Electrical Stimulation using PIC Microcontroller. *International Journal of Computer Applications* 44, 12 (2012), 31–35. <http://www.ijcaonline.org/archives/volume44/number12/6317-8662>
52. Steven Schirra and Frank R. Bentley. 2015. "It's kind of like an extra screen for my phone": Understanding Everyday Uses of Consumer Smart Watches. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA '15*. ACM Press, New York, New York, USA, 2151–2156. DOI: <http://dx.doi.org/10.1145/2702613.2732931>
53. Walter B. Shelley and Robert P. Arthur. 1957. The Neurohistology and Neurophysiology of the Itch Sensation in Man. *Archives of Dermatology* 76, 3 (sep 1957), 296–323. DOI: <http://dx.doi.org/10.1001/archderm.1957.01550210020004>
54. Donald A. Simone, Meenakshi Alreja, and Robert H. Lamotte. 1991. Psychophysical Studies of the Itch Sensation and Itchy Skin (“Alloknesis”) Produced by Intracutaneous Injection of Histamine. *Somatosensory & Motor Research* 8, 3 (jan 1991), 271–279. DOI: <http://dx.doi.org/10.3109/08990229109144750>
55. Sonja Ständer, Martin Steinhoff, Martin Schmelz, Elke Weisshaar, Dieter Metze, and Thomas Luger. 2003. Neurophysiology of Pruritus. *Archives of Dermatology* 139, 11 (nov 2003). DOI: <http://dx.doi.org/10.1001/archderm.139.11.1463>

56. Jürgen Steimle. 2016. Skin - The Next User Interface. *Computer* 49, 4 (apr 2016), 83–87. DOI: <http://dx.doi.org/10.1109/MC.2016.93>
57. Ashley M. Stewart, Christopher G. Pretty, and XiaoQi Chen. 2016. Design and Testing Of A Novel, Low-cost, Low-voltage, Functional Electrical Stimulator. In *12th IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications - MESA '16*. IEEE, 1–6. DOI: <http://dx.doi.org/10.1109/MESA.2016.7587155>
58. Atit Tamtrakarn. 2015. A Portable Switching Bi-Phasic Stimulator with Level-Shifting Inverter for Functional Electrical Stimulation Operating under a 6V Supply Voltage. In *TENCON 2015 - 2015 IEEE Region 10 Conference*. IEEE, 1–4. DOI: <http://dx.doi.org/10.1109/TENCON.2015.7373081>
59. Takara Tashiro and Atsuki Higashiyama. 1981. The perceptual properties of electrocutaneous stimulation: Sensory quality, subjective intensity, and intensity-duration relation. *Perception & Psychophysics* 30, 6 (1981), 579–586. DOI: <http://dx.doi.org/10.3758/BF03202013>
60. Robert P. Tuckett. 1982. Itch evoked by electrical stimulation of the skin. *The Journal of investigative dermatology* 79, 6 (1982), 368–373. DOI: <http://dx.doi.org/10.1111/1523-1747.ep12529734>
61. Graciela Unguez, Craig Duran, Delia Valles-Rosales, Michael Harris, Evan Salazar, Michael McDowell, and Wei Tang. 2015. 3D-printed Wearable Backpack Stimulator for Chronic in vivo Aquatic Stimulation. In *2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, 2147–2150. DOI: <http://dx.doi.org/10.1109/EMBC.2015.7318814>
62. T. Yokota, P. Zalar, M. Kaltenbrunner, H. Jinno, N. Matsuhisa, H. Kitanosako, Y. Tachibana, W. Yukita, M. Koizumi, and T. Someya. 2016. Ultraflexible organic photonic skin. *Science Advances* 2, 4 (2016), e1501856. DOI: <http://dx.doi.org/10.1126/sciadv.1501856>
63. Yang Zhang, Junhan Zhou, Gierad Laput, and Chris Harrison. 2016. SkinTrack: Using the Body As an Electrical Waveguide for Continuous Finger Tracking on the Skin. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems - CHI '16*. ACM Press, New York, New York, USA, 1491–1503. DOI: <http://dx.doi.org/10.1145/2858036.2858082>
64. Junhan Zhou, Yang Zhang, Gierad Laput, and Chris Harrison. 2016. AuraSense: Enabling Expressive Around-Smartwatch Interactions with Electric Field Sensing. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology - UIST '16*. ACM Press, New York, New York, USA, 81–86. DOI: <http://dx.doi.org/10.1145/2984511.2984568>