A Conceptual and Experimental Exploration of Electrovibration on the Palm and the Body

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***Abstract*— We present an exploration of electrovibration beyond the fingertip. We first explored the design space and feasibility of electrovibrating clothing and wearables, before pivoting to its use on rigid objects that our palms frequently brush against. We then conceptualized and sketched an electrovibrating keyboard that produces tactile feedback on the palms. To better understand the capabilities of this keyboard, we then conducted a psychophysical experiment with 14 participants to measure the detection thresholds of electrovibration at the palm and the fingertip. We found no statistically significant difference between the palm and fingertip, which suggests that the palm is an appropriate target for electrovibration.**

I. INTRODUCTION

Electrovibration modulates the friction experienced by the skin when sliding over a surface, creating programmable sensations of localized textures when coupled with tactile sensors. This effect is produced by applying an oscillating voltage to a conductive surface and feeling the surface through an electrically insulating layer [1].

This tactile feedback contributes to the improvement of user experience and human perception in interactive applications [1]. It also enhances user performance during gestural interactions [1]. This technology has wide application possibilities, including tools for persons with visual impairments, interactive children's books [2], and augmented visual surfaces with tactile feedback [1].

We propose extending electrovibration to clothing, wearables and smart objects that can stimulate parts of the hand and body other than the fingertip. We first present an exploration of the design space and feasibility of applying electrovibration through clothing and wearables (e.g., Figure 1). We then pivot to a similar exploration of rigid objects, with a focus on the palm as a sensitive target for electrovibration. We conclude this exploration with a proposal for an electrovibrating keyboard that produces tactile feedback as the palms accidentally or deliberately brush against its lower surface (see Figure 2).

While the effect of amplitude [3], frequency [2], and signal waveform [4] on the tactile perception of electrovibration at the fingertip has already been studied, we are not aware of any work that considered perception of electrovibration at the palm. We therefore conducted an experiment to investigate the perception of the electrovibration stimulus at the palm. More specifically, the experiment compares the absolute thresholds of electrovibration perception at the fingertip and

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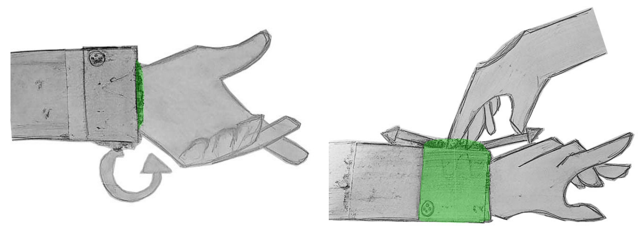
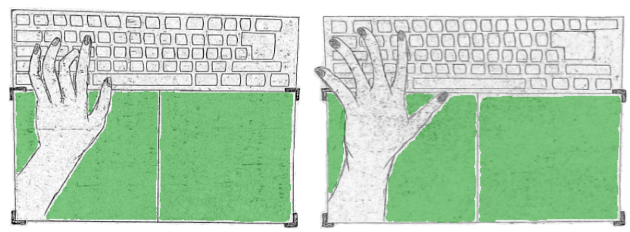


(a) (b)

Fig. 1: Examples of interactions with an electrovibrating cuff: (a) accidental interaction by natural movement and (b) deliberate interaction with the finger. Electrovibrating surface is shown in green.



(a) (b)

Fig. 2: Examples of interactions with an electrovibrating keyboard: (a) accidental interaction while typing and (b) deliberate interaction by brushing of the palm. Electrovibrating surface is shown in green.

at the palm for several frequencies. The results confirm that electrovibration should be easily perceptible on a keyboard that stimulates the palms.

II. BACKGROUND AND RELATED WORK

A. Electrovibration

Electrovibration generates tactile sensations by modulating the friction between the skin and an insulated conductive surface driven with time-varying high-voltage signals [5]. This technology has been widely used to produce programmable sensations as a finger slides on a touch screen (e.g., [1]).

Electrovibration has also been applied to interactions with everyday objects [6]. Reverse electrovibration, which consists of injecting the electrovibration signal on the user's body and grounding conductive objects, has been proposed as a practical solution in that context [6]. By sliding the fingers over the surface of the object, the user perceives distinct virtual tactile textures that augment the physical object [6]. Several applications have been proposed, including augmenting projected wall screens or physical impressions, communicating personalized and private messages on public touch screens, and providing a tactile guide against a wall for a person with visual impairments [6].

B. Perception of Electrovibration

The properties of the input signal influence the tactile perception of electrovibration. Negative and biphasic impulses, for example, are better perceived than positive impulses [7]. Square wave signals have lower sensory thresholds than sine waves for fundamental frequencies below 60 Hz. At higher frequencies, sine and square signals have similar sensory thresholds with a plateau until 480 Hz, followed by a steep increase [4]. At frequencies above 500 Hz, the electrovibrating threshold voltage was constant for square waveforms [4]. Perceptible frequencies range from 10 to 500 Hz [1]. Low frequencies provide the sensation of distant bumps, while high frequencies feel like fine textures [8], [1]. The pacinian corpuscles, which are most sensitive to vibrations at 250 Hz, are the main mechanoreceptors responsible for detecting the electrovibration stimulus [9].

The properties of the fingerpad and its contact with the surface are also known to affect perception of electrovibration. Humidity of the finger, for example, reduces the sensation of electrovibration [10]. The sensation of electrovibration also increases with applied force within a certain range [11], but can be dampened when using excessive force.

The properties of the electrovibrating surface's electrical insulation are also important. Varying the thickness of an insulating layer of poyamide between 4.7, 7.3 and 15.9 µm has been shown to have minimal effect on the threshold voltages of the sensation [12]. Using a dielectric insulator that is too thin or thick, however, can cause current to break through or the sensation to be imperceptible, respectively.

C. Tactile Perception on the Body

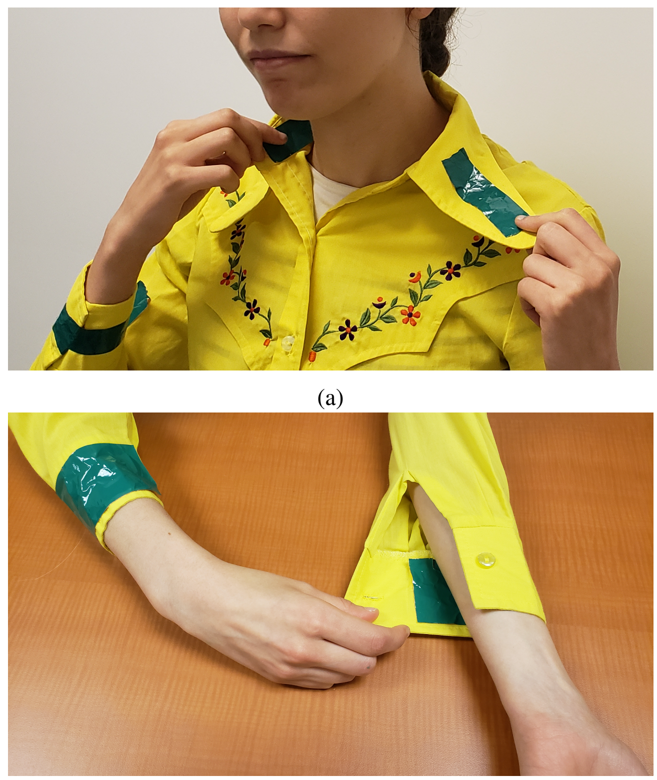
Vibrotactile perception is known to vary with the locus of the stimulus on the body [13]. [14], for example, studied the sensitivity to vibrotactile signals at body sites suitable for mobile and wearable haptic applications, such as the wrists, arms, thighs, feet, chest, belly, and spine. They compared the sensitivity of these sites with five vibration intensities, the presence or absence of a visual workload, while sitting in a chair or walking on a treadmill, and with or without knowledge of the location of the next stimuli. The results show that participants chose the wrists for notification applications, the arms and wrists for directional guidance, and the spine during exercise. Another notable finding was that the thighs were among the least effective and least preferred sites, despite their frequent use while a mobile phone is in a pocket.

III. Design Space Exploration

We explored the design space and feasibility of applying electrovibration first through clothing and wearables, and then through smart objects. We adopted a haptic sketching approach [15] to quickly iterate, and concluded with the proposal of an electrovibrating keyboard. Our exploration was partially documented in [16].

A. Electrovibrating Clothing and Wearables

We first explored the possibility and feasibility of applying electrovibration through clothing and wearables (e.g., Figure 3). We considered two forms of interaction (see Figure 1). In the first, users accidentally interact with the piece of clothing or wearable as they move naturally, brushing the skin of a part of their body against its electrovibrating inner surface. In the second, users deliberately interact with the clothing or wearable by purposefully moving their body against its electrovibrating inner surface or by running a finger against its electrovibrating outer surface. In many cases, interactions that are typically accidental could also be triggered by deliberate movements.



(a)

(b)

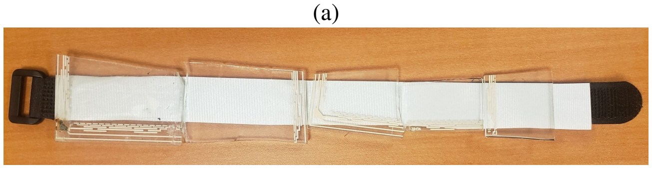
Fig. 3: Mock-up of flexible electrovibrating surfaces attached to the inner and outer surface of (a) a collar and (b) cuffs.

We developed haptic sketches with flexible conductive materials such as copper or aluminum foil and conductive textiles such as Velostat to investigate the perception of electrovibration on the body. We applied a thin layer of insulating paint and drove the materials with 100V signals at frequencies of 15 to 250 Hz. Safety precautions included current-limiting circuits (<5 mA), detachable connections, and user switches.

The flexible electrovibrating surfaces were intended to be attached to the inner and outer surface of clothing, as shown in mock-ups in Figure 3. We aimed for inner surfaces that are often brushed against while our body moves naturally (e.g., the collar or cuffs of a shirt), as well as outer surfaces that can easily be reached with a fingertip (e.g., the upper thighs of pants).

Fabricating flexible electrovibrating surfaces with reliable insulation and strong feedback at 100V proved challenging. We therefore also experimented with wearables made of multiple rigid surfaces. We found that capacitive glass plates (3M MicroTouch) could be cut using standard glass cutting techniques without damaging their electrode structure, which could be connected to at the edge of the glass. We created several haptic sketches, including an electrovibrating watch made of a single glass surface (Figure 4a), and an electrovibrating bracelet made of multiple cut-out plates (Figure 4b).

(a)



(b)

Fig. 4: Sketches of electrovibrating wearables made of cut capacitive plates: (a) watch and (b) bracelet.

Our preliminary results with these haptic sketches suggest that electrovibration is strongest and most noticeable on the palm and fingertips, and slightly weaker on the wrist. The arms, neck, and thighs produce a more subtle sensation and occasionally an unpleasant tingling, possibly due to the larger area of contact or the presence of hair. Moreover, we have found the sensations produced by natural movement of the body against an electrovibrating clothing or wearable (whether deliberate or accidental) to be difficult to distinguish from other tactile cues such as clothes brushing against the skin.

B. *Electrovibrating Objects*

A key finding from our exploration of electrovibrating clothing and wearables was that the palm seems to respond quite strongly to electrovibration. We therefore decided to further explore interactive concepts in which the palm naturally brushes against the surface of everyday objects. Inspired in part by [2], we quickly narrowed our investigation to the surface below a keyboard, such as the table underneath a keyboard or the lower surface of a laptop. We indeed observed that the palms are often resting or sliding against this surface as we write on a keyboard, offering an opportunity to transmit information by electrovibration.

We considered once again two forms of interactions with an electrovibrating keyboard: accidental interactions, where users naturally move their palm against the electrovibrating surface while writing or moving their hands to the mouse, and deliberate interactions where users purposefully rub their palm against the electrovibrating surface (see Figure 2).

We conducted brainstorms to identify applications for this electrovibrating keyboard. The most promising applications included:

- Notifications: The electrovibrating keyboard could display the source and importance of notifications without interrupting the user's main task. While typing, for example, the user could feel an important notification as a strong texture, or a less important notification as a discreet texture.
- Gaming: The electrovibrating keyboard could generate distinguishable, localized textures while the player types on the keyboard. This feedback could, for example, be used to locate enemies or to detect if a boundary is crossed.

We implemented a simple sketch of the electrovibrating keyboard by combining a commercial keyboard (Logitech K380) with two capacitive plates (3M MicroTouch), as shown in Figure 5.

Fig. 5: Sketch of electrovibrating keyboard made with an off-the-shelf keyboard and two capacitive plates.

IV. Experiment

A more detailed study comparing the tactile perception of eletrovibration on the palm and fingertips is necessary to better understand the capabilities of the electrovibrating keyboard proposed in the previous section. We therefore conducted a psychophysical study to compare the perception of electrovibration on the fingertip and palm.

A. *Experimental Apparatus*

1) Electrovibration Signal Generator: The signal generator consisted of a Raspberry Pi, a high precision AD/DA board, and a high-voltage amplifier.

The Raspberry Pi was chosen for its small size and reasonable price. The AD/DA board (Waveshare, China) adds high precision digital/analog and analog/digital conversion functions to the Raspberry Pi. This board has a 2-channel DAC chip (DAC8552) that enables the generation of analog signals. We used it to produce programmable signals with control over amplitude, frequency and waveform. Since the DAC8552 was designed for unipolar operation, we added an OPA703 amplifier to allow a bipolar output range (see DAC8552 datasheets for more details).

We programmed the Raspberry Pi to produce maximum voltages of $\pm$2V. The output of the Raspberry Pi was then amplified by a high-voltage power amplifier with a gain of 50V/V (Trek 2205, Trek Inc.). The signal generator therefore produced voltages in the range of $\pm$100V.

The participants wore an antistatic wrist strap attached to the signal generator's ground. Although our body can naturally serve as a ground, this grounding bracelet provides better safety and increases the strength of the sensations produced by electrovibration [1].

2) Safety Precautions: Several precautions were taken to ensure the safety of the participants. A 20 kΩ high-voltage resistor was placed at the output of the signal generator to limit the current to which participants could be exposed to 5 mA at the maximum voltage of 100V. A brief exposure to such a low current is known to be of no danger for humans. The participants' movements were also unrestricted and therefore contact with the electrovibrating surface could easily be broken in the event of an insulator breakdown, ensuring that any exposure to currents would be very brief.

In an abundance of caution, the output of the signal generator could also be interrupted by pressing a large push button or by releasing a foot pedal. Participants pressed on the foot pedal to activate the output, and the experiment facilitator could press the push button at any time.

3) Experimental Setup: The signal generator was used to drive an electrovibrating surface made of a capacitive touchpad (3M MicroTouch). In order to better control the location touched, an area was left exposed and the rest was covered with tape.

The electrovibrating surface was mounted on a load cell so that the force applied by the finger or palm could be monitored. The load cell was connected to the Raspberry Pi through a 24-bit precision analog-to-digital converter (HX711). The force applied was displayed with a visual gauge shown a computer screen (see Figure 6).

The electrovibrating surface could be touched with the fingertip or palm. To reduce fatigue and improve comfort, participants placed their arm on an armrest while touching the surface with their dominant hand.

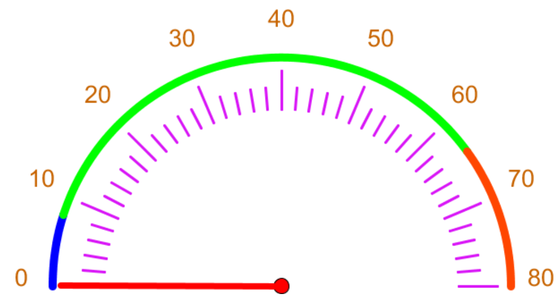


Fig. 6: Visual gauge showing the force applied against the surface. Participants were instructed to remain in the green range.

A wireless keypad was used by participants to input their responses during the experiment. An oscilloscope was finally used by the experiment facilitator to monitor the system output during the experiment.

The complete experimental setup is shown in Figure 7.

Fig. 7: Experimental setup including electrovibrating surface, load cell, signal generator, keypad and computer monitor.

B. *Procedure and Participants*

To study how our detection threshold varies with different parts of the hand, we conducted an absolute detection experiment. Through such experiments, we can determine the minimum voltage amplitude that an observer can detect. We seek to compare the detection thresholds of a sinusoidal signal at different frequencies, on the fingertip and palm.

1) Participants: We conducted the experiment with 14 participants (seven female) having a mean age of 27.5 years. They were all students at our institution (ÉTS).

The participants disinfected their hands before starting the experiment. The touch surface and all device components were also cleaned with alcohol before their arrival. The participants completed and signed a consent form and a pre-questionnaire before the experiments. The experimental protocol was approved by the ÉTS Research Ethics Committee.

2) Methodology: We conducted the experiment in a dedicated room. The experiment investigated the effect of hand placement on the tactile perception by electrovibration. The study, similar in methodology to that of [4], consisted of determining the absolute detection thresholds of a sinusoidal signal at 5 frequencies (15, 30, 60, 120, and 240 Hz), with stimulation at two locations (fingertip and palm). These frequencies were randomly generated.

The participants wore a headset playing white noise and an antistatic wristband. Their arm was supported by an armrest to ensure a comfortable posture.

3) Procedure: The participants were invited to slide their index finger or palm on the touch surface. They were told to press a button on the keypad to alternate between a state with the electrovibrating stimulus and a state without any stimulus. The transition from one state to the other was supported by visual feedback on a computer screen. The participants were allowed to alternate between the two states as many times as they wished, and were told to press another button when they believed the current state displayed the electrovibrating stimulus. The experiment then moved to the next trial.

Throughout the experiment, the participants were asked to maintain a force between 0.1 N and 0.6 N, which is within the typical range of forces used for tactile exploration [17]. They were able to monitor the force using a visual gauge displayed on the screen of a computer (Figure 6). They were also asked to interact naturally with the surface and to use a comfortable hand posture.

The experiment was conducted using the adaptive staircase method (one up/two down), which provides accurately estimated detection and discrimination thresholds with a relatively small number of trials [4], [1]. We started the tests with an amplitude of 100V, allowing a perceptible sensation for all participants. The voltage amplitude of the new stimulus was then adaptively adjusted based on a participant's previous responses. If the participant gave two correct responses, the signal amplitude decreased by 10V. If the participant gave one incorrect response, the signal amplitude increased by 10V. After three inversions (defined as a switch from correct to incorrect, or the reverse), the step size was decreased by 2V. We stopped the experiment after 12 reversals and estimated the absolute detection threshold as the average of the last 12 reversals [1]. The procedure is exemplified in Figure 8 with the data from one complete staircase.

This procedure was applied once for a first hand location (fingertip or palm) at all frequencies, and then again for the other location. The order of hand locations was counterbalanced, with half of the participants doing the experiment with the fingertip first and the other with the palm first.

C. Results

Figure 9 and Figure 10 show the absolute detection thresholds of the electrovibration stimulus across participant on the fingertip and the palm. We notice a higher detection threshold at the palm for 10 of the 14 participants, and a higher mean detection threshold at that location. The median detection thresholds are nevertheless similar at both locations, with a much greater variance in thresholds at the palm. A one-way repeated measures ANOVA confirms that there is no statistically difference in absolute detection threshold between the fingertip and the palm ($F(1, 26) = 2.252, p = 0.145$).

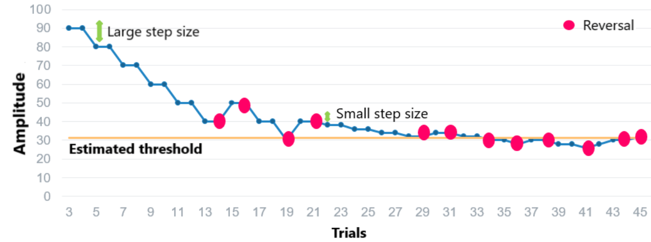


Fig. 8: Example of data collected by the "one up, two down" adaptive staircase method.

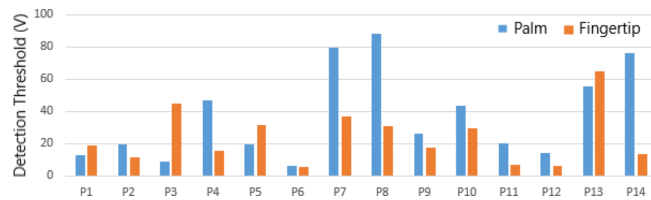


Fig. 9: Absolute detection thresholds for each participant (P1-P14) on the fingertip and the palm.

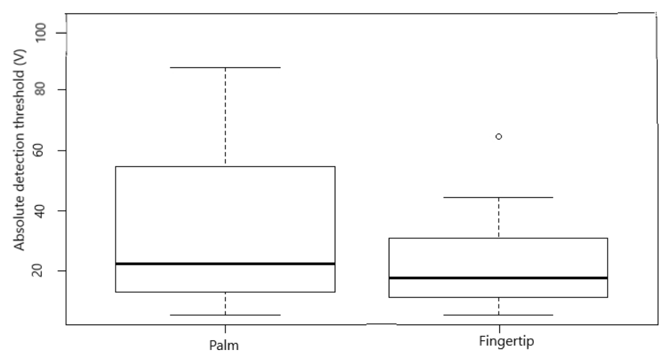


Fig. 10: Absolute detection thresholds for the fingertip and palm across participants.

We note that two participants had difficulty completing the experiment and may have responded differently than the others. The first participant had a good perception of the stimulus at the fingertip, but could not feel it on the palm even at high amplitude. The second participant expressed difficulty in concurrently pressing the foot pedal, sliding against the surface, and monitoring the applied applied force. No statistically significant differences were found after removing these two outliers.

D. Discussion

The purpose of this study was to determine the effect of the hand areas on the tactile perception of electrovibration. We found no statistically significant difference between the perception thresholds of electrovibration at the palm and fingertip.

Our results are in agreement with those of [4], which found an absolute detection threshold of 24.5V for sinusoidal signals at the fingertip, with frequencies of 15, 30, 60, 120 and 240 Hz. We obtained a very similar detection threshold of 23.8V at the fingertip with the same waveform and frequencies.

Our results suggest that the palm is very sensitive to electrovibration. This is perhaps not surprising given that the palm is rich in the mechanoreceptors that are responsible for the perception of the electrovibration stimulus [18]. They also suggest that the sensitivity of the palm to electrovibration is similar to that of the fingertip, which is surprising given the much greater density of rapidly adapting mechanoreceptors in the fingerpad compared to the palm [18]. Repeating the experiment with a larger sample size may reveal a statistically-significant difference in sensitivity to electrovibration at these two locations.

We also noticed a significantly higher variance in detection thresholds in the palm, compared to the fingertip. This may be the result of inter-individual differences in sensitivity, or of variations in the hand posture used to slide the palm against the surface. This result suggests that it may be more difficult to obtain consistent results across users when targeting the palm as opposed to the fingertip.

These results nevertheless confirm that electrovibration can be felt very strongly at the palm, and suggest that the tactile stimulus provided by an electrovibrating keyboard could easily be felt. While not tested directly in this work, we can also hypothesize that electrovibration may be able to produce textures and other tactile features on the palm with a similar richness as what has been demonstrated on the fingertip.

V. Conclusion

This paper first explored the design space and feasibility of applying electrovibration on clothing, wearables, and on smart objects. We found that electrovibration is difficult to produce reliably on clothing due to their flexibility, and that its feedback is often masked by other haptic cues present in clothing and wearables. We noticed, however, that the palm is quite sensitive to electrovibration and pivoted to an exploration of objects against which the palm brushes. We proposed and sketched an electrovibrating keyboard capable of producing feedback on the palms as they move accidentally or deliberately against it.

To better understand the capabilities of this keyboard, we then conducted an experiment to compare the detection threshold of electrovibration at the fingertip and the palm. We used a "one up, two down" adaptive staircase method to determine the absolute detection threshold of electrovibration at five frequencies and two hand locations (fingertip and palm). Our results reveal no statistically significant effect of the hand region on the tactile perception of electrovibration. We conclude that the palm is very sensitive to electrovibration, and that our concept of an electrovibrating keyboard should produce strong, rich tactile sensations on the palm.

Our future work will consist of implementing a fully-functional prototype of the electrovibrating keyboard, developing exemplar applications to demonstrate the added value of the haptic feedback that it will produce in practical contexts, and validating the concept with user experiments.

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