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SparkTouch: Contactless Haptic Spatial Patterns on the Palm and Fingertip using Electric Sparks

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***Abstract*—Contactless haptic technologies deliver tactile feedback remotely, eliminating the need for direct skin contact and reducing setup time. However, current technologies have relatively weak intensity or coarse perception resolution. This paper proposes SparkTouch, an approach exploring the use of electric arcs for delivering contactless spatio-temporal patterns in the palm and fingertip. We first quantified the perceptibility of electric sparks as a function of frequency and hand location. We then conducted a spatio-temporal pattern recognition study (n = 30), where we measured user's discrimination accuracy for sparks moving along the palm and fingertip for 14 patterns, including lines and shapes of different directions. Results show that (1) accuracy is similar to other contactless methods, (2) discrimination between lines or shapes is over 85%, and (3) their direction can be detected. This study is the first to investigate contactless spatio-temporal haptic patterns on the fingertip; and we demonstrate (4) an equivalent recognition accuracy between fingertip and palm, making electric arcs a promising technology for mid-air haptics on the fingertip. Altogether, SparkTouch paves the way for future fine contactless haptics, with envisioned scenarios such as contactless mid-air interaction with public kiosks or keypads.**

***Index Terms*—Contactless Haptics, Electric Spark, High-Voltage, Pattern Recognition, Spatio-Temporal Patterns, Mid-Air**

I. Introduction

Contactless haptic technologies are a convenient way to provide tactile feedback in mid-air interaction techniques. This is needed for the come-and-interact paradigm, so that users do not need to put on, wear or touch different devices. Additionally, contactless haptic technologies fit better in environments where hygiene is critical and physical contact should be avoided, such as hospitals or public spaces [1].

Currently, focused ultrasound is the most widespread contactless haptic technology, with companies providing off-the-shelf devices and toolkits (e.g. UltraLeap Ltd, PixieDust Inc. or eMerge). An array of ultrasonic emitters can focus and modulate ultrasonic waves at different points in space that, upon contact with the user's palm, induce tactile sensations [2], [3]. This tactile feedback is used to convey direction [4], [5],

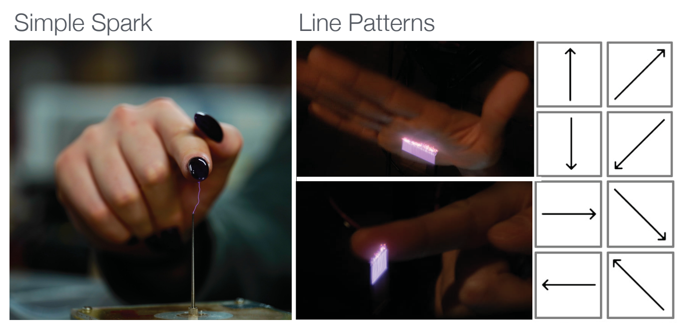

Fig. 1. *SparkTouch* uses electric sparks to deliver contactless haptic spatio-temporal patterns. Left) Regular spark being applied on a fingertip. Right) Long exposure photos of a line pattern traced on the palm and index fingertip.

compliance [6], temperature [7] or spatial haptic patterns [8]–[10]. However, focused ultrasound presents some drawbacks, such as reduced intensity [11] and coarse resolution [12], thus spatial patterns can only be applied on the palm.

In this paper, we investigate the use of electric arcs as an alternative technology for contactless haptics, especially for the recognition of finer spatio-temporal haptic patterns. We propose *SparkTouch*, an approach to provide contactless tactile patterns through the use of a spark generated by a Tesla coil that is controllably displaced to trace different shapes on the palm and fingertips.

Tesla coils generate high-voltage, low current and high frequency alternating current electric arcs that are safe to touch. These arcs have already been used to stimulate the fingertip [13], but were only investigated subjectively, in terms of comfort, intensity or pain.

In this paper, we quantified sparks intensity perception thresholds under different frequencies (n = 6). The sparks were applied on two different hand parts, the palm and the fingertip. They both present a high density of mechano-receptors while offering, respectively, a bigger surface or higher spatial acuity. We empirically show that spatio-temporal patterns are similarly perceived on the palm and the fingertip.

We then conducted a pattern recognition user study (n = 30) where lines and shapes with various directions were traced with electric sparks on the users' palms and index fingertip. This study was approved by the ethics, data protection and biosecurity committee of the university (PI-011/22) and conducted according to the pertinent legislation.

To the best of our knowledge, it is the first time that spatio-temporal pattern recognition on the fingertip is achieved via contactless stimulation. Results show that (1) *SparkTouch* offers comparable accuracy to contact based technologies [14], [15] and contactless ultrasound based systems [8], [16] on the palm; (2) palm and fingertip showed equivalent recognition accuracy; (3) discrimination between lines or shapes and (4) their directionality can be performed using electric sparks.

Taken altogether, *SparkTouch* offers novel opportunities for contactless haptic patterns, with envisioned use-cases such as mid-air interaction with public kiosks or intangible keypads.

The contributions of this paper are:

- *SparkTouch*, an approach to deliver contactless tactile spatio-temporal patterns through the use of a spark;
- A customized Tesla coil capable of providing mid-air haptics with controllable modulation frequency, intensity and duration along configurable paths;
- Empirical results quantifying intensity perception thresholds depending on frequency and hand location (palm and fingertip);
- Empirical results showing *SparkTouch*'s accuracy for pattern recognition on the palm **and** fingertip.

II. Related Work

Mid-air interaction techniques have been elicited through numerous studies and defined as *intuitive* [17], usually involving hand or body gestures, coupled with tracking devices. They enable contactless selection and manipulation of digital content on distant [18], floating 2D displays [19] or in 3D environments such as AR [20], [21] or VR [22], [23]. However, mid-air interaction suffers from the of lack haptic feedback.

To fully benefit from the freedom of mid-air gestures and interaction techniques, solutions to provide haptics without grounded, tethered or handheld apparatuses are being investigated. The most common solutions are wearable technologies [24], worn on the users' hands, wrist or fingers. Haptic wearables either apply forces on the users (e.g., exoskeletons [25]), or stimulate them through vibrations [26], pressure [27], skin stretch [28], tangible props [29] or electrotactile signals [30]. However, wearables have a set-up time, do not fit all hands or finger sizes [31] and can feel cumbersome, heavy or impairing depending on their form factor. Thus, other alternatives investigate the use of mid-air haptic devices [32], providing contactless yet perceivable haptic stimulation.

Contactless haptic technologies provide haptic stimuli "without direct physical contact or the need to wear a device that may disrupt feelings of immersion" [32]; and therefore are in-line with the come-and interact paradigm, where a user can just approach and start interacting with a digital interface. Contactless technologies include various technologies, such as lasers, able to induce warmth or prickling sensations [33] from a distance; or air jets, that provide tactile sensations [34] when deforming the skin [35]. Focused ultrasound has been extensively investigated [1], both in research and industry. It can provide perception of contact with intangible screens [19], direction [4] or spatial haptic patterns [16].

Current contactless systems, and more specifically focused ultrasounds, have shown positive results for pattern recognition [8], [16], [36], [37] or Braille symbols [9]. However, they are exclusively applied on the palm. Focused ultrasound have a limited point-localization resolution [10], [12], which cannot provide a signal fine enough to trace a distinguishable pattern on the fingertip.

So far, only contact-based technologies have investigated the use of haptic patterns for the fingertips, using wearables, such as pin-arrays [38], electrotactile [39], hydraulic patches [40] or pump arrays [41]. However, to the best of our knowledge, no research has been conducted to elicit contactless tactile patterns on the fingertip.

In contrast to ultrasound technology, electric arcs could provide a finer and sharper stimuli than the ultrasonic focal point. Spelmezan et al. described the sensation of plasma as "sharp" or "prickling" [13], which suggests that sparks have the potential to achieve higher resolutions compared to ultrasound.

As opposed to electrotactile feedback [42], [43], electric arcs can produce stimuli from a distance. They rely on the ionization of air to generate a plasma channel in mid-air that transfers current. Electric arcs can stimulate the nerves while also stimulating thermoreceptors, through their high temperature. By tweaking its amplitude and pulse frequency, and similarly to electrotactile feedback [44], electric arcs could provide both temperature or vibration, tickling and pinprick sensations; in a safe and touchless way. Sparks were only investigated subjectively [13], in terms of perceptibility, comfort, intensity, pain and stress.

In this paper, we explore the use of electric sparks for delivering contactless haptic spatio-temporal patterns on the palm and, **for the first time** using contactless technologies, on the fingertip.

III. System

SparkTouch relies on a modified off-the-shelf pancake Tesla coil to generate high-voltage, low current, high-frequency alternating current electricity, which creates safe-to-touch electric arcs, or *sparks*.

A. Generating and Controlling Sparks

The spark generation system consists of an off-the-shelf modified commercial pancake tesla coil with a resonant frequency of $\approx$ 4.3MHz, powered at 48 V with a power consumption of up to 1.2 A. It includes a PWM signal generator, which triggers the sparks at a given frequency and duty cycle. We integrated our own custom signal generator using an ESP32 microcontroller to provide higher frequencies and duty cycle resolutions from a computer. This modification allowed for a more precise modulation of the spark (time resolution of up to 1 μs). Frequency, duty cycle and durations were controlled from the computer; with the duty cycle, we control the intensity (see Figure 2).

The commercially available Tesla coil main power MOSFET has a 12 V logic level, thus to drive it we connected it to a IXDN602P1 MOSFET driver IC, which takes the 3.3 V signal from the ESP32 (see Figure 2).

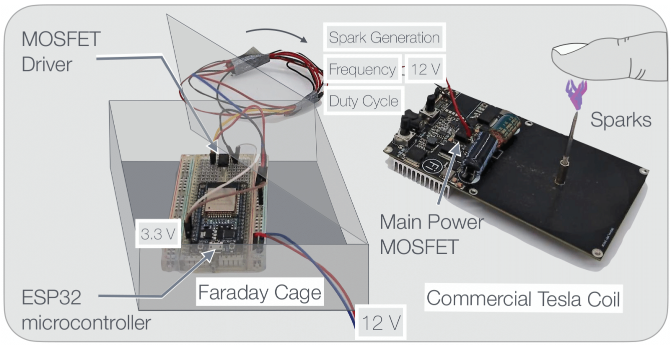

Fig. 2. *SparkTouch*'s hardware: (Left) in a Faraday cage, we connect an ESP32 to a MOSFET Driver IC (3.3 V $\leftrightarrow$ 12 V); which we use to trigger (Right) the main power MOSFET of a modified commercially available Tesla coil. Sparks generated with controlled frequency and duty cycle from a computer.

B. Reducing Interferences

Mitigating electromagnetic interference is crucial to protect the microcontroller and provide a stable signal generation, especially in an environment with high electromagnetic radiation, such as the proximity of a Tesla coil. We hence placed the microcontroller and MOSFET driver inside a Faraday cage (see Figure 2), reducing electromagnetic interference caused by the 4.3 Mhz carrier wave of the Tesla coil. Also, to minimise electrical noise, the input of the MOSFET driver was pulled down with a 10kΩ resistor, while the output was pulled down with a 47Ω resistor.

C. Fine-tuning Spark Contact Point

Sparks tend to spread and branch out to reach a contact point (see Figure 3 - Left). The further away the contact point, the wider the spread and therefore the larger the stimulation area. It is thus important to constrain and adjust the distance between the electrode and its future contact point. Constraining the stimulation area was achieved in Sparkle [13] by getting the electrode as close as possible to the fingertip, through a fine mesh guiding it. Differently, we inserted a flexible PTFE tube on the electrode to constrain and guide the spark over a larger distance (3 cm long tube, 1.5 cm on the electrode). By having the end of the tube closer to the skin, we ensure a minimum distance between the electrode and the stimulated area (see Figure 3 - Right). Keeping a minimum distance is important because the spark is perceived as unpleasant when it is touched close to the electrode (below 5 mm), also the Tesla coils detune and lose performance if the finger is too close to the electrode. Furthermore, the tube avoids the electrode piercing the skin if the user accidentally presses upon it.

D. Safety

The circuit and high-voltage transformer were in an acrylic case to prevent users from accidentally touching it. The only part left exposed was the electrode, although a PTFE tube was inserted into it to ensure a minimum distance between the user and the tip. Additionally, a hollow plastic cylinder was placed around the electrode, its height was slightly larger than that of the electrode. We also follow the guidelines for high-voltage gathered by Sparkle [13]: (1) using a power supply with regulated voltage and current limit and (2) limit the maximum charge of the capacitors on the electronics.

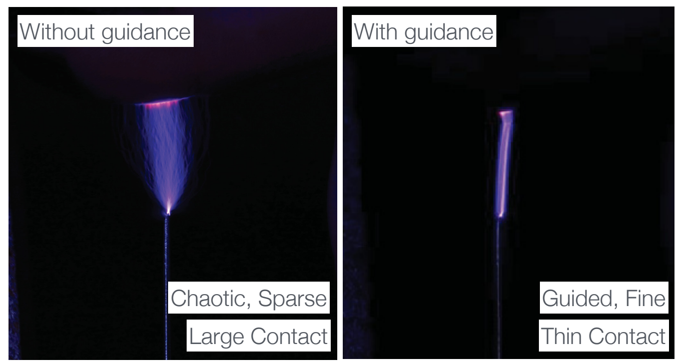

Fig. 3. Long-exposure photographs of *SparkTouch* stimuli with (left)/without (right) PTFE tube guiding the spark.

IV. Preliminary Intensity Perception Thresholds

The aim of this user study is to analyse the perception threshold as a function of the stimuli position (e.g., fingertip, palm) and modulation frequency. Sensitivity is known to be different for point localization, two-point discrimination and other psychophysics properties [45]–[47], therefore we decided to verify whether body part had an effect on spark perception and sensitivity.

As mentioned in Section III, the intensity is controlled here using the duty cycle – i.e. the fraction of one period in which a signal or system is active – over a duration (e.g., a 1 Hz signal with an *intensity* or *duty cycle* of 10 with a duration of 10 seconds would mean the spark is generated every second for 100 ms, for 10 seconds).

A. Apparatus

We used the electric sparks hardware presented in Section III, hidden from the users' by a black fabric that occluded their view (see Figure 4). Users were asked to place their arm over an adjustable platform, which aim was two-fold: (a) allowing the users to rest their arm and keeping it still during the experience; (b) ensuring the finger and palm distances to the PTFE tube were consistent between users (5 mm). Users employed their right hand to control a mouse to answer on a laptop in front of them. Participants wore noise-cancelling headphones playing brown noise to mask the overall system noise when it sparks.

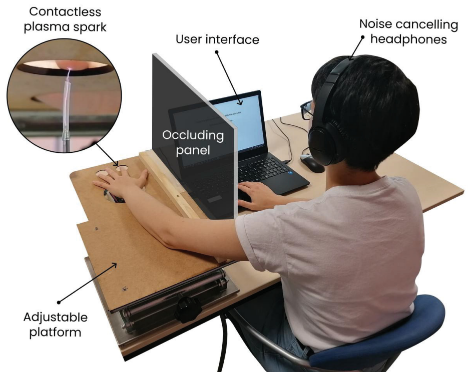

Fig. 4. Setup used for the intensity perception threshold study. The user, wearing noise-cancelling headphones, is sat down in front of a computer and uses it to provide answers. Separated by an opaque panel, their arm is placed on an adjustable armrest, above the electrode tip of the Tesla coil.

B. Procedure

Participants were told about the purpose of the study and signed an informed consent form. They positioned themselves at a desk as per Figure 4; and were asked to wipe their fingertip and palm with a cotton-soaked with alcohol, to have similar skin conditions between participants. They moved their left arm over the adjustable platform to feel comfortable and placed their fingertip and palm above the respective holes. They were asked to provide their answers (e.g., intensity threshold) with their right hand on the keyboard.

They finally were requested to wear noise-cancelling headphones and the experiment started. The experiment duration was on average 30 minutes.

C. Method

To define the intensity perception threshold, we employ the methods of limits [48], by either increasing or decreasing each prior stimulus' duty cycle (e.g., intensity) by 1 unit (e.g., 1 μs) every 2s. The starting condition (decreasing ↓ or increasing ↑) was chosen randomly.

Users were asked to press the space bar on the ascending series (↑) when they started feeling the applied stimulus; and when they stopped feeling it on the descending ones (↓).

D. Participants

We recruited six participants (self-reported gender, 4 female; 2 male), aged 23 to 56 years old (average = 35.7, std = 15). None of them presented any physical or tactile impairments. Two of them had previously experienced contactless haptic stimuli. Handedness was not regarded in this study.

E. Conditions

We investigate the effects of stimuli FREQUENCY and POSITION on intensity thresholds in this study. We chose 2 FREQUENCIES (45 Hz and 225 Hz), as they are between the threshold ranges of the Meissner and Pacini mechanoreceptors respectively [49]–[51], which are most likely to be excited by *SparkTouch*. We initially tested lower (8 Hz - Merkel [51]) and higher (1000 Hz - nociceptors) frequencies but they were discarded respectively for poor perception or burning sensation. The stimuli duration was set at 0.25 s. We chose 2 POSITIONS: the index fingertip and the palm; known to show different sensitivities [47]. All participants had to go through 3 BLOCKS of 2 SERIES (↑ and ↓). The stimuli POSITION was alternated in order to avoid satiety effects from continuous stimulation.

F. Design

We used a within-subjects design for this study. The global experiment can be summarised as: 6 PARTICIPANTS $\times$ 2 FREQUENCIES $\times$ 2 POSITIONS $\times$ 2 SERIES $\times$ 3 BLOCKS $=$ 144 TRIALS.

G. Results

We analysed the data using a 2×2 repeated measures ANOVA (POSITION×FREQUENCY), and a one-way ANOVA analysis on BLOCKS. We verified ANOVA's assumptions (normality, equal variances), and computed posthocs pairwise T-tests with Bonferroni-corrected p-values.

1) Global Effects: Overall, we noted two main effects during this study. A first significant effect was noted for FREQUENCY ($F_{(1,5)} = 12.3, p_{GG} < 0.05, \eta_p^2 = 0.71$); and a second small but significant effect was noted for BLOCKS ($F_{(1.26,6.29)} = 7.7, p_{GG} < 0.05, \eta^2 = 0.61$). No effect was noted for POSITION. Moreover, there was no cross-effect between the conditions.

2) Frequency Effect: The intensity threshold was significantly higher ($p < 0.05$) for 45 Hz (average = 11.1 μs, std = 9.4 μs) than for 225 Hz (average = 6.5 μs, std = 5.5 μs) - see Figure 5 - A.

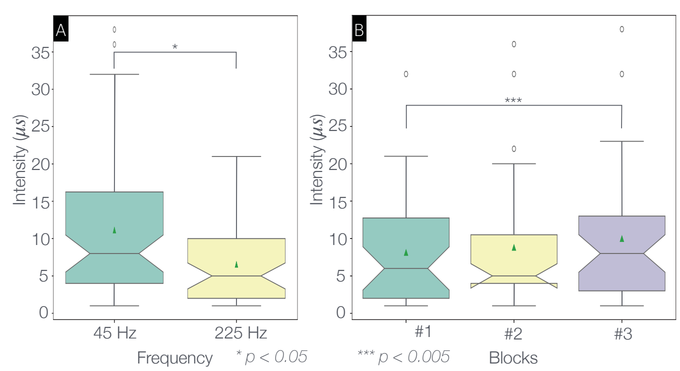

Fig. 5. Results for the Intensity Threshold user study. A. Boxplot of Intensity thresholds as a function of FREQUENCIES; B. Boxplot of Intensity thresholds as a function of BLOCKS. Significance levels are annotated (*: $p < 0.05$, ***: $p < 0.005$).

3) Position Effect: As there was no significant effect on POSITION, we ran a TOST (two one-side T-tests) to evaluate whether results are equivalent for both positions (non-significance means the effect is not big enough to be anything other than a chance finding; TOST means the effect is zero and samples are similar and equivalent), with an interval of $[-4, 2]$ raw scores. A significant result for equivalence was obtained with $t_{(98.47)} = 1.72, p < 0.05$, 90% CI = $[-3.91, 1.20]$.

4) Block Effect: We noted a significant effect ($p < 0.005$) between the first and last blocks, the intensity thresholds were 8.1 μs (std = 7.6 μs) and 10.0 μs (std = 8.8 μs) respectively - see Figure 5 - B).

5) Global Results: Apart from the global effects and average results, we note that the 90^{th} centile for the 45 Hz and the 225 Hz frequencies respectively was 23 μs and 13.9 μs, we can therefore use stimuli with intensity above 25 μs (for 45 Hz) and 15 μs (for 225 Hz) to ensure their perceptibility.

H. Discussion

1) Position Effect: We showed that the stimuli position (at least between the fingertip and the palm) does **not** have an effect on the intensity perception thresholds. As opposed to the other psychophysics parameters (e.g., point localization, two-point threshold, shift etc), we did not note a significant effect of position for spark-related haptics; and results suggested that the intensity perception thresholds were equivalent with an interval window of 4μs. This result is in-line with our scope, aiming to provide patterns onto both the palm (as per most of contactless literature) **and** the fingertip.

2) Frequency Effect: We demonstrated that the frequency did have a significant effect on intensity perception thresholds. The higher the frequency, the lower intensity needs to be to be perceptible.

3) Block Effect: We also noted an effect over time using *SparkTouch*. Similarly to electrotactile stimuli – where the system needs to be recalibrated over time to remain perceptible [52] – the more time spent using sparks, the higher the intensity perception thresholds. This means that, over time, we would probably need to recalibrate the intensity threshold to ensure *SparkTouch*'s perceptibility.

4) Limitations to Fixed Duration: Our results are dependent on frequency but also on stimulus duration. Using other signal durations, these parameters could change, with stimuli feeling more intensely [13].

V. Spatio-Temporal Patterns Recognition

The aim of this study is to measure the accuracy of spatio-temporal pattern recognition using *SparkTouch*; and to compare its accuracy with other haptic technologies: contact and contactless.

A. Apparatus

The spark generation setup is similar to the previous study. Additionally, the Tesla coil is mounted on an inverted delta stage (BIQU Kossel) to move the spark generator along controlled paths (see Figure 6).

B. Participants

We recruited 30 participants (self-reported gender, 15 female and 15 male), aged 19 to 33 years old (average = 25.5, std = 4.3). None of them presented any physical nor tactile impairments. Two of them had previously experienced contactless haptic stimuli, but never involving electric sparks. Handedness was not considered in this study.

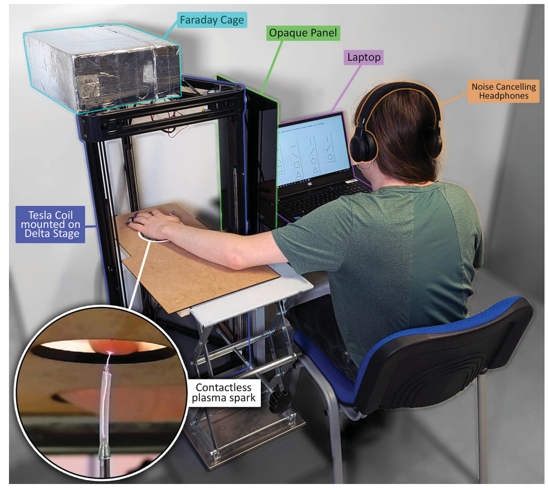

Fig. 6. Setup for the spatio-temporal pattern recognition study.

C. Experiment Design Rationale

1) Frequencies, Positions, and Intensities: For this study, we selected the same frequencies and body parts as in the intensity perception thresholds study. However, when first experimenting the spatio-temporal patterns, a burning sensation could be felt; mainly due to the duration of the pattern tracing (duration effect seen in [13]). To reduce this sensation, we had two options: reducing the duration of each stimulus, to get discrete patterns; or reducing their intensities and keep drawing pseudo-continuous patterns. Pseudo-continuous stimuli refers to discrete stimuli applied at a frequency that makes them be perceived as continuous by the user. Previous research using focused ultrasound has shown that pseudo-continuous signals significantly improve performance in hand pattern recognition [16]. We thus decided to reduce the stimuli intensities and use pseudo-continuous drawing patterns.

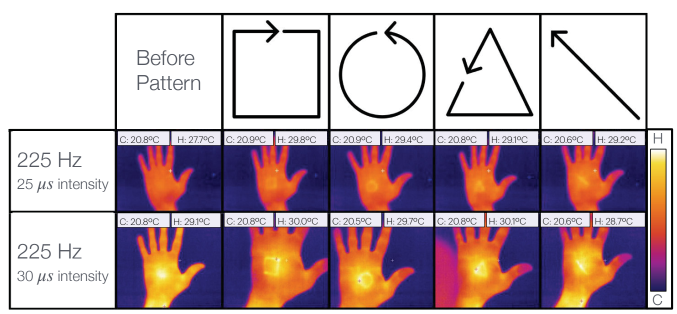

Fig. 7. Thermography of a hand before and after receiving a contactless pattern using *SparkTouch* at different intensities. We note that the higher the intensity, the hotter the skin (H: hottest; C: coldest).

We show in Figure 7 images of a hand before and after different shape patterns with a thermal camera. We note that the higher the intensity, the higher the skin temperature; and therefore the perception of heat. Stimuli traced for more than 4 seconds with 30 μs intensity could be unpleasant due to temperature increase.

From the perception thresholds study, we found that intensity parameters had to be at least above 25 μs for 45 Hz, and 15 μs for 225 Hz. We thus decided in this study to set the frequencies and intensity levels at 45 Hz to 25 μs for the palm and 35 μs for the finger; and at 225 Hz to 15 μs on the palm. When applying patterns at 225 Hz on the finger, the system frequently crashed despite the shielding, thus we decided to remove it from the study.

2) Patterns: For selecting the patterns, we considered different papers involving haptic pattern recognition: surface haptics [53], wearable haptics [54], and electrotactile [39] stimuli. We integrated some of the patterns into a set of 14 patterns. As per [53], patterns included straight lines in 8 directions (NE-E-ES-S-SW-W-NW, N), and shapes (circles, squares; and triangles as per [54]) traced clockwise and counter-clockwise (see Figure 8 for the shapes, and Figure 1 for the lines).

a) Pattern Size: Most haptic patterns studies fix the size of the patterns (e.g., circles of 5, 10 or 15 cm [55], or 6.4 cm [16]), however sensitivity is not homogenous on the palm and fingertips, due to the different densities of receptors within the skin [47]. We thus decided to adjust the patterns to the size of the user hand and fingertip. Each line and shape are circumscribed in a circle, which centre and diameter are dependent of the desired stimulated area (procedure is described below).

b) Speeds: With contactless technologies such as ultrasounds, speeds vary in the literature from 2 m/s [16] to 7 m/s [36], with patterns being traced in 2 seconds [8]. However, in some occasions these speeds were considered too fast. With surface haptics (e.g., contact technologies), slower speeds were used with arrays of tactors stimulating the palm: from 150 mm/s to 300 mm/s [53] with larger pattern sizes (10 cm), and patterns being traced in approximately 4 seconds. In this study, we choose speeds that made patterns be traced in approximately 4 seconds; which results in speeds of 38 mm/s for the palm and 11 mm/s for the fingertip.

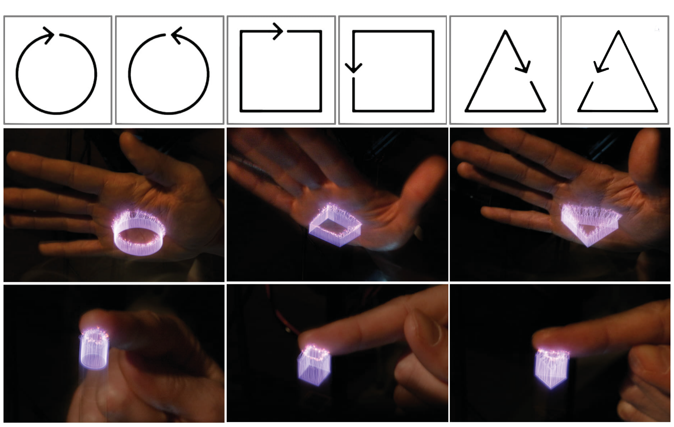

Fig. 8. Shapes used for the spatio-temporal patterns recognition study. (Up) Shape patterns. (Down) Long exposure photos of the patterns applied on the palm and the fingertip.

D. Conditions

Patterns were applied on 2 POSITIONS: the palm and the index fingertip. Regarding FREQUENCIES, the palm was stimulated at both 225 Hz and 45 Hz; and fingertip at 45 Hz. We chose 14 PATTERNS, including LINES with 8 DIRECTIONS; and 3 SHAPES with 2 DIRECTIONS. Each participant performed 3 BLOCKS in a pseudo-random order.

E. Procedure

Participants were first informed of the purpose of the study and signed an informed consent form. They were then asked to sit in front of a table and to rest their left arm on the platform (see Figure 6). They were asked to wear noise-cancelling headphones. When the participant first rested their hand onto the platform, we adjusted the electrode to the centre of the palm. We moved the electrode forward until reaching the knuckles (from below), then moved 3 mm backward towards the centre. We recorded this second position. These two positions define a circle, in which all the lines and shapes are inscribed. A similar procedure was performed for the fingertip (going to the end of the fingertip and backwards 5 mm).

The system would trace a pattern and the user had to select the perceived pattern on a computer screen using a mouse with their right hand. The average duration of the study was 48 minutes (std = 12 minutes).

F. Design

We used a within-subjects design, and alternated the POSITIONS (1. PALM – 45 HZ, 2. FINGER – 45 HZ, 3. PALM – 225 HZ) to avoid raising the intensity perception thresholds from training – as showed in the preliminary study.

The experiment can be summarised as 30 PARTICIPANTS $\times$ (1 POSITION $\times$ 2 FREQUENCIES + 1 POSITION $\times$ 1 FREQUENCY) $\times$ 14 PATTERNS $\times$ 3 BLOCKS = 3780 TRIALS.

G. Results

We computed repeated-measures ANOVA for both FREQUENCY and POSITION (comparing respectively exclusively results in the palm, or results exclusively with 45 Hz).

1) Global Effects: We found a significant effect on FREQUENCY ($F_{(1,29)} = 7.9, p < 0.005, \eta^2 = 0.21$), but did not note any effect on either POSITION nor BLOCK.

2) Block Effect: Even though we noted no significant differences between blocks, accuracy went down between trials (resp. 45.7%, 41.1% and 43.4%).

3) Accuracy: We discuss global results based on our conditions: Position, Frequency, Pattern types and their Direction. We do however display more detailed results of the accuracy of the task as confusion matrices; for the conditions PALM - 225 HZ in Figure 9 and FINGERTIP – 45 HZ in Figure 10.

a) Position: The results are quite comparable depending on the stimulated area. The results were slightly (but not significantly) higher in the palm (average = 45.2%) than in the fingertip (average = 39.8%). We ran a TOST (two one-side T-tests) to evaluate whether accuracies are equivalent for both positions. A significant result for equivalence was obtained with $t_{(864.9)} = -2.54, p < 0.01$, 90% CI = -8.79 to -1.92.

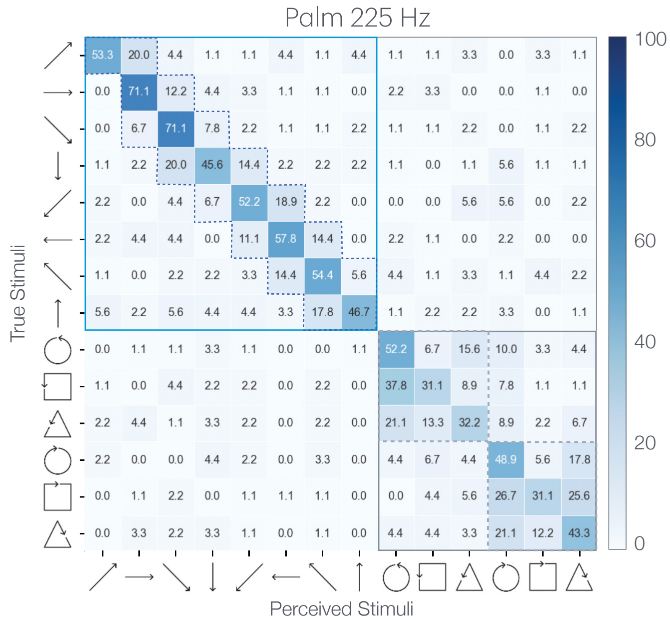

Fig. 9. Confusion Matrix of the Pattern Recognition user study, PALM position, 225 HZ frequency. Rectangles outline Lines and Shapes. Dotted areas outline orientations.

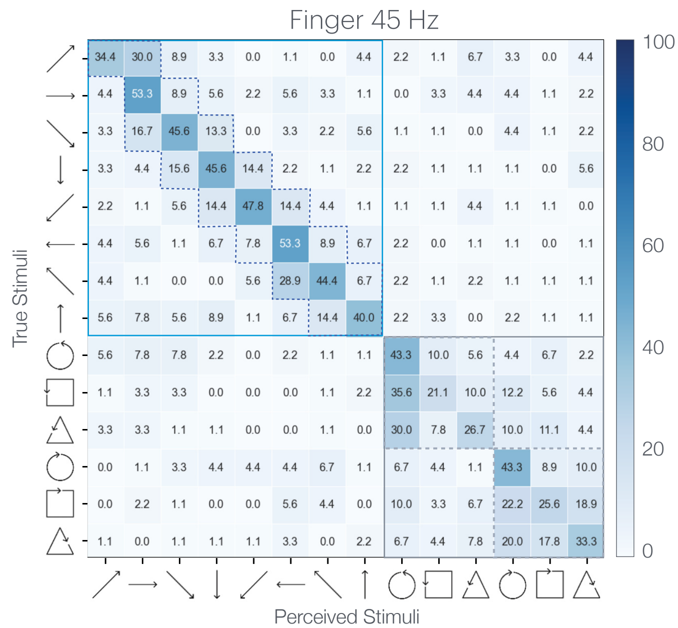

Fig. 10. Confusion Matrix of the Pattern Recognition user study, FINGER position, 45 HZ frequency. Rectangles outline Line and Shape recognition. Dotted areas outline orientations.

b) Frequency: The recognition was significantly higher at 225 Hz (average = 49.3%) than it 45 Hz (average = 41.0%) ($p < 0.005$).

c) Pattern: Regarding patterns, participants could discriminate whether lines were drawn with 88.8% accuracy and shapes with 85.7%. This can be noted in our confusion matrices Figure 9 - 10, where we highlighted this discrimination using squares (blue for the lines, grey for the shapes). However, the global accuracy for lines was about 49.8% while for shapes it was 34.8%; most of the confusion occurred in their direction (see below).

d) Direction: To differentiate the direction discrimination, we split here the lines and shapes. First, and as illustrated at Figure 9 - 10 in the dotted grey areas, even though shapes were not always recognized, their direction was. We indeed note an 85.8% average accuracy for discriminating the right direction in shapes.

For the lines, almost half of them were discriminated in their correct direction (49.9%) - but, as illustrated in the dotted blue areas (Figure 9 - 10), lines often got confused with their nearest-neighbour. Indeed, by allowing a slightly larger tolerance ($\leq \frac{\pi}{4}$ for the nearest-neighbour), the accuracy goes up to 81.9%.

Focusing on the fingertip, we reach 83.7% accuracy in discriminating the shape direction, and a 81.0% for near-neighbour lines.

H. Discussion

Accuracy compared to literature. Our accuracy is comparable to results in the literature, for instance with contact-haptics using vibrotactile on the edge of a phone [14] (44% accuracy with 32 patterns - lines and shapes). Accuracy is slightly lower than surface haptics patterns [53] – from which our patterns were originally inspired – showing $\approx$ 58% accuracy for 14 patterns. However, they provided feedback to their users with the answers correctness, leading to improving results over time. In our study, no training nor confirmation of correctness was provided.

Regarding contactless technologies, a smaller set of patterns are employed (e.g., 4×4 directions [8], [16], [36]), with approximately similar results than the ones we demonstrated on the palm.

On the fingertip, the accuracy of *SparkTouch* is a bit lower than the contact-based results (e.g., wearable electrotactile [39], only 3 lines and 3 shapes, above 70% accuracy); however, these results are encouraging for more investigation of contactless haptic spatio-temporal patterns on the fingertip.

Fingertip Performances. We demonstrate in this study how applying sparks on the fingertips can go further than perceptibility, tingling or heat sensations [13], and can indeed convey information such as spatio-temporal patterns. Our accuracy results on the fingertip showed no significant differences with the results in the palm; and suggested that the accuracies for both positions were equivalent with an interval window of 8%. Moreover, palm results showed comparable results to the literature. While an effect was shown on frequency (with better results for 225 Hz), we could not perform the 225 Hz study on the fingertip, as the long stimuli duration coupled with the low dampening of the delta stage for the fingertip area caused it to crash. Alternatives to the delta stage are mentioned in Section VI. We however do believe that haptic patterns on the fingertip hold great potential and that fine-tuning parameters will allow more accuracy.

Shapes. We showed that participants could differentiate shapes from lines, and their directions; however the discrimination of the shape itself could be increased. Contactless technologies such as ultrasounds mentioned how edges are hard to differentiate (e.g., a square from a circle or a triangle) [1] and propose guidelines to improve performance. Reducing the speeds around the corners could benefit haptic shape identification.

Directions. We showed that participants could demonstrate with high accuracy whether they felt a shape or a line, and their direction. We took into account the nearest-neighbour pattern to show the participants' confusion within the lines. Apart from intensity threshold calibration (Section IV), we believe that defining and quantifying spatial and temporal acuities using electric sparks would benefit this accuracy. We demonstrated that a high resolution can be achieved with electric sparks, thus fine-tuning the length of the lines could improve this line direction discrimination.

Satiety effect. As per our first study and as seen with ultrasounds and electrotactile [52], a satiety effect can occur, with performance and sensitivity going down over time.

VI. Limitations and Future Work

We envision various directions for future work, to alleviate some of *SparkTouch*'s limitations and to expand its scope.

Guiding the Sparks for Spatial Acuity Thresholds. There was still significant spread of the spark on the contact point with the skin, also the end of the tube had to be relatively close to the skin. Quantifying the spatial acuity when perceiving the spark could help to improve *SparkTouch*'s overall usability, by revealing if smaller contact areas lead to more acuity. If so, using ultrasounds [56] or blowing air could help to direct the spark and reduce the contact area, as it is done in cold plasma treatments [57].

Different Carrier. The off-the-shelf Tesla coil had a resonant frequency fixed around 4.3 MHz. We adjusted the modulation frequency, duty cycle and duration but we did not explore different carrier frequencies. We note that we tried various Tesla coils with different carrier frequencies and the sensations seemed dominated by the modulation frequency, duty cycle and duration; nonetheless a systematic study should be performed in the future.

Skin Conductivity Compensation. We did not adjust the intensity of the stimuli to compensate for skin conductivity nor capacitance of each user. The state of the art in electrotactile technology measures those characteristics and adjusts accordingly the intensity of the stimuli to provide uniform perception across users [58], [59].

Mid-air Multimodal Haptics. Electric stimuli can be combined with other contactless haptic stimulations, such as ultrasounds, air-jets, or infrared radiation. The combination of sparks and air-jets could mitigate the burning sensation produced by the spark, while its combination with ultrasound could potentially increase the realism of mid-air interaction techniques; e.g., ultrasound would be applied for soft contact with a mid-air button whereas the electric spark for a sharper click when activated.

Stimuli Hedonics. Although the sensations produced by the electric arcs has been studied by Spelmezan et al. [13], and further investigated in our work, findings remain non-conclusive. We were unable to identify the mechanoreceptors or nocireceptors responsible for the tingling or heat sensations. Moreover, the causes for the pleasantness or discomfort caused by the stimuli can be explored in detail to identify suitable parameters to maximize perceived intensity and pleasantness, while avoiding discomfort and pain. A study with electromyography could identify the stimulation receptors, although carrying it out may be difficult due to the high electrical noise in close proximity to a tesla coil.

Integration and Interaction. Integrating *SparkTouch* with hand tracking systems to explore active haptics, for example to apply stimuli when the user reaches into a mid-air button or object [60]. Contactless feedback like pricking sensation has not been explored to help users be more alert or cautious before performing a risky task or action, such as crossing the street. A sharp pin prick sensation could potentially be delivered to a user pressing a non-tangible button for turning the light green on a cross-walk. Being able to deliver directions can enhanced the interactions with a mid-air keyboard, apart from receiving a point sensation on the finger that presses a virtual key, a direction can be conveyed towards the next predicted letter. In a mid-air kiosk, a left-to-right line can be applied when pressing the next button, right-to-left for previous button, and a square for OK. After several uses, the user could operate the kiosk eyes-free and just get haptic confirmation from the pressed button.

Miniaturization and Various Electrodes. Future work could guide the spark without the delta stage, for example guiding it with electrostatic deflection. Also, novel form-factors can be investigated to make *SparkTouch* portable and/or with a more lightweight integration. We envision to increase the number of electrodes to build an array (such as contact-based pin-array [38]), enabling for instance to provide two sparks at the same time. This could enable applications like contactless Braille by applying various simultaneous stimulation points.

Non-Glabrous Skin. We studied haptic patterns on glabrous skin (fingertip, palm). However, we note that electric sparks are also perceived in non-glabrous skin such as in the back of the hand or forearm.

VII. Conclusion

Contactless haptic technologies deliver tactile feedback remotely, in-line with the come-and-interact paradigm, where users are not disrupted by a device nor limited by hygienic restrictions. In this paper, we propose *SparkTouch*, an approach to deliver contactless haptic spatio-temporal patterns (lines, shapes) using electric sparks. We leverage the generation of spatio-temporal haptic patterns onto the palm (shown with other contactless haptics), but more importantly, we propose for the first time to extend it to the fingertip.

Spark intensity was first quantified in a perception threshold study (n = 6) and different modulation frequencies (45 and 225 Hz) were tested. We then conducted a pattern recognition study (n = 30), and analysed user's recognition accuracy of spatio-temporal patterns traced on the palm and fingertip. The recognition accuracy was similar or slightly worse than contact-based methods and similar to focused ultrasound, the most used contactless method. No significant difference was noted between palm and fingertip recognition performance, indicating that electric arcs are a promising method for delivering fine contactless spatio-temporal patterns.

Future work includes making the stimulus intensity user-dependent, exploring methods to guide the spread of the spark to an even finer mm-scale, and combining *SparkTouch* with other contactless technologies (such as air-jets or ultrasounds).

Electric arcs show a great potential to enhance tactile feedback with mid-air interfaces, and we envision future use-cases such as contactless Braille reading, interaction with public kiosks or contactless keypads.

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References

[1] O. Georgiou, W. Frier, and O. Schneider, "User Experience and Mid-Air Haptics: Applications, Methods, and Challenges," in *Ultrasound Mid-Air Haptics for Touchless Interfaces*, O. Georgiou, W. Frier, E. Freeman, C. Pacchierotti, and T. Hoshi, Eds. Cham: Springer International Publishing, 2022, pp. 21–69.

[2] T. Carter, S. A. Seah, B. Long, B. Drinkwater, and S. Subramanian, "UltraHaptics: Multi-Point Mid-Air Haptic Feedback for Touch Surfaces," 2013.

[3] I. Rakkolainen, E. Freeman, A. Sand, R. Raisamo, and S. Brewster, "A Survey of Mid-Air Ultrasound Haptics and Its Applications," *IEEE Transactions on Haptics*, vol. 14, no. 1, pp. 2–19, Jan. 2021, conference Name: IEEE Transactions on Haptics. [Online]. Available: https://ieeexplore.ieee.org/document/9174896/?arnumber=9174896

[4] L. Mulot, T. Howard, C. Pacchierotti, and M. Marchal, "Ultrasound Mid-Air Haptics for Hand Guidance in Virtual Reality," *IEEE Transactions on Haptics*, vol. 16, no. 4, pp. 497–503, Oct. 2023, conference Name: IEEE Transactions on Haptics. [Online]. Available: https://ieeexplore.ieee.org/document/10107446/?arnumber=10107446

[5] G. Reardon, B. Dandu, Y. Shao, and Y. Visell, "Shear shock waves mediate haptic holography via focused ultrasound," *Science Advances*, vol. 9, no. 9, p. eadf2037, 2023.

[6] Q. Sun, M. Zhang, Y. Makino, and H. Shinoda, "Expanding softness and hardness sensations in mid-air ultrasonic haptic interfaces combining amplitude and spatiotemporal modulation," *IEEE Access*, pp. 1–1, 2024, conference Name: IEEE Access. [Online]. Available: https://ieeexplore.ieee.org/document/10718306/?arnumber=10718306

[7] S. Villa, Y. Weiss, N. Hirsch, and A. Wiethoff, "An Examination of Ultrasound Mid-air Haptics for Enhanced Material and Temperature Perception in Virtual Environments," *Proceedings of the ACM on Human-Computer Interaction*, vol. 8, no. MHCI, pp. 1–21, Sep. 2024. [Online]. Available: https://dl.acm.org/doi/10.1145/3676488

[8] D. Hajas, D. Pittera, A. Nasce, O. Georgiou, and M. Obrist, "Mid-air haptic rendering of 2d geometric shapes with a dynamic tactile pointer," *EEE Trans. Haptics*, vol. 13, no. 4, p. 806–817, Oct. 2020. [Online]. Available: https://doi.org/10.1109/TOH.2020.2966445

[9] V. Paneva, S. Seinfeld, M. Kraiczi, and J. Müller, "Haptiread: Reading braille as mid-air haptic information," in *Proceedings of the 2020 ACM designing interactive systems conference*, 2020, pp. 13–20.

[10] E. Freeman and G. Wilson, "Perception of ultrasound haptic focal point motion," in *Proceedings of the 2021 International Conference on Multimodal Interaction*, 2021, pp. 697–701.

[11] E. Freeman, S. Brewster, and V. Lantz, "Tactile feedback for above-device gesture interfaces: Adding touch to touchless interactions," in *Proceedings of the 16th International Conference on Multimodal Interaction*, ser. ICMI '14. New York, NY, USA: Association for Computing Machinery, 2014, p. 419–426. [Online]. Available: https://doi.org/10.1145/2663204.2663280

[12] G. Wilson, T. Carter, S. Subramanian, and S. A. Brewster, "Perception of ultrasonic haptic feedback on the hand: localisation and apparent motion," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '14. New York, NY, USA: Association for Computing Machinery, 2014, pp. 1133–1142. [Online]. Available: https://dl.acm.org/doi/10.1145/2556288.2557033

[13] D. Spelmezan, D. R. Sahoo, and S. Subramanian, "Sparkle: Hover Feedback with Touchable Electric Arcs," in *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, ser. CHI '17. New York, NY, USA: Association for Computing Machinery, 2017, pp. 3705–3717. [Online]. Available: https://dl.acm.org/doi/10.1145/3025453.3025782

[14] J. Seo and S. Choi, "Edge flows: Improving information transmission in mobile devices using two-dimensional vibrotactile flows," in *2015 IEEE World Haptics Conference (WHC)*. IEEE, Jun. 2015, p. 25–30. [Online]. Available: http://dx.doi.org/10.1109/WHC.2015.7177686

[15] M. Jeannin, A. B. Dhiab, C. Hudin, and S. Panëels, "Dynamic Pattern Recognition with Localised Surface Haptics and Apparent Motion," in *2023 IEEE World Haptics Conference (WHC)*, Jul. 2023, pp. 474–480, iSSN: 2835-9534. [Online]. Available: https://ieeexplore.ieee.org/document/10224427/?arnumber=10224427

[16] L. Mulot, T. Howard, C. Pacchierotti, and M. Marchal, "Improving the Perception of Mid-Air Tactile Shapes With Spatio-Temporally-Modulated Tactile Pointers," *ACM Transactions on Applied Perception*, p. 3611388, Jul. 2023. [Online]. Available: https://dl.acm.org/doi/10.1145/3611388

[17] P. Vogiatzidakis and P. Koutsabasis, "Gesture Elicitation Studies for Mid-Air Interaction: A Review," *Multimodal Technologies and Interaction*, vol. 2, no. 4, p. 65, Dec. 2018, number: 4 Publisher: Multidisciplinary Digital Publishing Institute. [Online]. Available: https://www.mdpi.com/2414-4088/2/4/65

[18] L.-W. Chan, H.-S. Kao, M. Y. Chen, M.-S. Lee, J. Hsu, and Y.-P. Hung, "Touching the void: direct-touch interaction for intangible displays," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. Atlanta Georgia USA: ACM, Apr. 2010, pp. 2625–2634. [Online]. Available: https://dl.acm.org/doi/10.1145/1753326.1753725

[19] Y. Monnai, K. Hasegawa, M. Fujiwara, K. Yoshino, S. Inoue, and H. Shinoda, "HaptoMime: mid-air haptic interaction with a floating virtual screen," in *Proceedings of the 27th annual ACM symposium on User interface software and technology*, ser. UIST '14. New York, NY, USA: Association for Computing Machinery, Oct. 2014, pp. 663–667. [Online]. Available: https://dl.acm.org/doi/10.1145/2642918.2647407

[20] H. Benko, R. Jota, and A. Wilson, "MirageTable: freehand interaction on a projected augmented reality tabletop," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. Austin Texas USA: ACM, May 2012, pp. 199–208. [Online]. Available: https://dl.acm.org/doi/10.1145/2207676.2207704

[21] O. Hilliges, D. Kim, S. Izadi, M. Weiss, and A. Wilson, "HoloDesk: direct 3d interactions with a situated see-through display," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '12. New York, NY, USA: Association for Computing Machinery, 2012, pp. 2421–2430. [Online]. Available: https://dl.acm.org/doi/10.1145/2207676.2208405

[22] I. Poupyrev, S. Weghorst, M. Billinghurst, and T. Ichikawa, "A framework and testbed for studying manipulation techniques for immersive VR," in *Proceedings of the ACM symposium on Virtual reality software and technology - VRST '97*. Lausanne, Switzerland: ACM Press, 1997, pp. 21–28. [Online]. Available: http://portal.acm.org/citation.cfm?doid=261135.261141

[23] J. J. LaViola Jr., "3D Gestural Interaction: The State of the Field," *International Scholarly Research Notices*, vol. 2013, no. 1, p. 514641, 2013, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1155/2013/514641. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1155/2013/514641

[24] C. Pacchierotti, S. Sinclair, M. Solazzi, A. Frisoli, V. Hayward, and D. Prattichizzo, "Wearable Haptic Systems for the Fingertip and the Hand: Taxonomy, Review, and Perspectives," *IEEE Transactions on Haptics*, vol. 10, no. 4, pp. 580–600, Oct. 2017, conference Name: IEEE Transactions on Haptics.

[25] I. Choi, E. W. Hawkes, D. L. Christensen, C. J. Ploch, and S. Follmer, "Wolverine: A wearable haptic interface for grasping in virtual reality," in *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. Daejeon, South Korea: IEEE, Oct. 2016, pp. 986–993. [Online]. Available: http://ieeexplore.ieee.org/document/7759169/

[26] E. Pezent, A. Israr, M. Samad, S. Robinson, P. Agarwal, H. Benko, and N. Colonnese, "Tasbi: Multisensory Squeeze and Vibrotactile Wrist Haptics for Augmented and Virtual Reality," in *2019 IEEE World Haptics Conference (WHC)*. Tokyo, Japan: IEEE, Jul. 2019, pp. 1–6. [Online]. Available: https://ieeexplore.ieee.org/document/8816098/

[27] A. Girard, M. Marchal, F. Gosselin, A. Chabrier, F. Louveau, and A. Lécuyer, "HapTip: Displaying Haptic Shear Forces at the Fingertips for Multi-Finger Interaction in Virtual Environments," *Frontiers in ICT*, vol. 3, Apr. 2016.

[28] C. Pacchierotti, G. Salvietti, I. Hussain, L. Meli, and D. Prattichizzo, "The hRing: A wearable haptic device to avoid occlusions in hand tracking," in *2016 IEEE Haptics Symposium (HAPTICS)*, Apr. 2016, pp. 134–139, iSSN: 2324-7355.

[29] E. Bouzbib, M. Teyssier, T. Howard, C. Pacchierotti, and A. Lécuyer, "PalmEx: Adding Palmar Force-Feedback for 3D Manipulation with Haptic Exoskeleton Gloves," *IEEE Transactions on Visualization and Computer Graphics*, pp. 1–8, 2023, conference Name: IEEE Transactions on Visualization and Computer Graphics.

[30] S. Vizcay, P. Kourtesis, F. Argelaguet, C. Pacchierotti, and M. Marchal, "Electrotactile Feedback in Virtual Reality For Precise and Accurate Contact Rendering," *arXiv:2102.00259 [cs]*, Jan. 2021, arXiv: 2102.00259. [Online]. Available: http://arxiv.org/abs/2102.00259

[31] E. Young, D. Gueorguiev, K. J. Kuchenbecker, and C. Pacchierotti, "Compensating for Fingertip Size to Render Tactile Cues More Accurately," *IEEE Transactions on Haptics*, pp. 1–1, 2020. [Online]. Available: https://ieeexplore.ieee.org/document/8960410/

[32] I. Rakkolainen, E. Freeman, A. Sand, R. Raisamo, and S. Brewster, "A Survey of Mid-Air Ultrasound Haptics and Its Applications," *IEEE Transactions on Haptics*, pp. 1–1, 2020. [Online]. Available: https://ieeexplore.ieee.org/document/9174896/

[33] E. Ammendola, G. Tancredi, K. Ricci, G. Falcicchio, M. Valeriani, and M. de Tommaso, "Assessment of c fibers evoked potentials in healthy subjects by nd: Yap laser," *Pain Research and Management*, vol. 2022, no. 1, p. 7737251, 2022.

[34] A. Christou, R. Chirila, and R. Dahiya, "Pseudo-hologram with aerohaptic feedback for interactive volumetric displays," *Advanced Intelligent Systems*, vol. 4, no. 2, p. 2100090, 2022.

[35] M. Bianchi, J. C. Gwilliam, A. Degirmenci, and A. M. Okamura, "Characterization of an air jet haptic lump display," in *2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. IEEE, 2011, pp. 3467–3470.

[36] T. Howard, G. Gallagher, A. Lécuyer, C. Pacchierotti, and M. Marchal, "Investigating the recognition of local shapes using mid-air ultrasound haptics," in *2019 IEEE World Haptics Conference (WHC)*, 2019, pp. 503–508.

[37] B. Long, S. A. Seah, T. Carter, and S. Subramanian, "Rendering volumetric haptic shapes in mid-air using ultrasound," *ACM Transactions on Graphics*, vol. 33, no. 6, pp. 1–10, Nov. 2014. [Online]. Available: https://dl.acm.org/doi/10.1145/2661229.2661257

[38] Y. Ujitoko, T. Taniguchi, S. Sakurai, and K. Hirota, "Development of finger-mounted high-density pin-array haptic display," *IEEE Access*, vol. 8, pp. 145 107–145 114, 2020.

[39] W. Lin, D. Zhang, W. W. Lee, X. Li, Y. Hong, Q. Pan, R. Zhang, G. Peng, H. Z. Tan, Z. Zhang, L. Wei, and Z. Yang, "Super-resolution wearable electrotactile rendering system," *Science Advances*, vol. 8, no. 36, p. eabp8738, 2022. [Online]. Available: https://www.science.org/doi/abs/10.1126/sciadv.abp8738

[40] E. Leroy and H. Shea, "Hydraulically amplified electrostatic taxels (haxels) for full body haptics," *Advanced Materials Technologies*, vol. 8, no. 16, p. 2300242, 2023.

[41] V. Shen, T. Rae-Grant, J. Mullenbach, C. Harrison, and C. Shultz, "Fluid reality: High-resolution, untethered haptic gloves using electroosmotic pump arrays," in *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology*, ser. UIST '23. New York, NY, USA: Association for Computing Machinery, 2023. [Online]. Available: https://doi.org/10.1145/3586183.3606771

[42] K. Kaczmarek, J. Webster, P. Bach-y Rita, and W. Tompkins, "Electrotactile and vibrotactile displays for sensory substitution systems," *IEEE Transactions on Biomedical Engineering*, vol. 38, no. 1, pp. 1–16, 1991.

[43] H. Kajimoto, N. Kawakami, S. Tachi, and M. Inami, "Smarttouch: electric skin to touch the untouchable," *IEEE Computer Graphics and Applications*, vol. 24, no. 1, pp. 36–43, 2004.

[44] M. E. Altinsoy and S. Merchel, "Electrotactile feedback for handheld devices with touch screen and simulation of roughness," *IEEE Transactions on Haptics*, vol. 5, no. 1, pp. 6–13, 2012.

[45] J. M. Loomis and C. C. Collins, "Sensitivity to shifts of a point stimulus: An instance of tactile hyperacuity," *Perception & Psychophysics*, vol. 24, no. 6, pp. 487–492, Nov. 1978. [Online]. Available: http://link.springer.com/10.3758/BF03198771

[46] J. M. Loomis, "Tactile Pattern Perception," *Perception*, vol. 10, no. 1, pp. 5–27, Feb. 1981. [Online]. Available: http://journals.sagepub.com/doi/10.1068/p100005

[47] S. Weinstein, "Intensive and Extensive Aspects of Tactile Sensitivity as a Function of Body Part, Sex, and Laterality," in *The Skin Senses*, D. Kenshalo, Ed., 1968, oCLC: 239118.

[48] L. A. Jones and H. Z. Tan, "Application of Psychophysical Techniques to Haptic Research," *IEEE Transactions on Haptics*, vol. 6, no. 3, pp. 268–284, Jul. 2013, conference Name: IEEE Transactions on Haptics.

[49] M. A. Piccinin, J. H. Miao, and J. Schwartz, "Histology, meissner corpuscle," 2018.

[50] J. Scheibert, S. Leurent, A. Prevost, and G. Debrégeas, "The role of fingerprints in the coding of tactile information probed with a biomimetic sensor," *Science*, vol. 323, no. 5920, pp. 1503–1506, 2009.

[51] D. Deflorio, M. Di Luca, and A. M. Wing, "Skin and mechanoreceptor contribution to tactile input for perception: A review of simulation models," *Frontiers in Human Neuroscience*, vol. 16, 2022. [Online]. Available: https://www.frontiersin.org/journals/human-neuroscience/articles/10.3389/fnhum.2022.862344

[52] S. Vizcay, P. Kourtesis, F. Argelaguet, C. Pacchierotti, and M. Marchal, "Design, evaluation and calibration of wearable electrotactile interfaces for enhancing contact information in virtual reality," *Comput. Graph.*, vol. 111, no. C, p. 199–212, Apr. 2023. [Online]. Available: https://doi.org/10.1016/j.cag.2023.01.013

[53] M. Jeannin, A. B. Dhiab, C. Hudin, and S. Panëels, "Dynamic Pattern Recognition with Localised Surface Haptics and Apparent Motion," in *2023 IEEE World Haptics Conference (WHC)*. Delft, Netherlands: IEEE, Jul. 2023, pp. 474–480. [Online]. Available: https://ieeexplore.ieee.org/document/10224427/

[54] L. Kuang, M. Aggravi, P. R. Giordano, and C. Pacchierotti, "Wearable cutaneous device for applying position/location haptic feedback in navigation applications," in *2022 IEEE Haptics Symposium (HAPTICS)*, 2022, pp. 1–6.

[55] W. Frier, D. Ablart, J. Chilles, B. Long, M. Giordano, M. Obrist, and S. Subramanian, "Using spatiotemporal modulation to draw tactile patterns in mid-air," in *Haptics: Science, Technology, and Applications: 11th International Conference, EuroHaptics 2018, Pisa, Italy, June 13-16, 2018, Proceedings, Part I 11*. Springer, 2018, pp. 270–281.

[56] J. Irisarri, I. Ezcurdia, N. Iriarte, M. Sirkka, D. Nikolaev, J. Mäkinen, A. Martinez-Marchese, D. Iablonskyi, A. Salmi, and A. Marzo, "Electric plasma guided with ultrasonic fields," *Science Advances*, vol. 11, no. 6, p. eadp0686, 2025. [Online]. Available: https://www.science.org/doi/abs/10.1126/sciadv.adp0686

[57] S. K. Pankaj and K. M. Keener, "Cold plasma: Background, applications and current trends," *Current Opinion in Food Science*, vol. 16, pp. 49–52, 2017.

[58] Z. Zhou, Y. Yang, J. Liu, J. Zeng, X. Wang, and H. Liu, "Electrotactile perception properties and its applications: A review," *IEEE Transactions on Haptics*, vol. 15, no. 3, pp. 464–478, 2022.

[59] M. Rahimi, F. Jiang, and Y. Shen, "Non-linearity of skin properties in electrotactile applications: Identification and mitigation," *IEEE Access*, vol. 7, pp. 169 844–169 852, 2019.

[60] E. Freeman, "Ultrasound haptic feedback for touchless user interfaces: Design patterns," in *Ultrasound Mid-Air Haptics for Touchless Interfaces*. Springer, 2022, pp. 71–98.