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TacTex: A Textile Interface with Seamlessly-Integrated Electrodes for High-Resolution Electrotactile Stimulation

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TacTex: A Textile Interface with Seamlessly Integrated Electrodes for High-Resolution Electrotactile Stimulation

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ABSTRACT

This paper presents TacTex, a textile-based interface that provides high-resolution haptic feedback and touch-tracking capabilities. TacTex utilizes electrotactile stimulation, which has traditionally posed challenges due to limitations in textile electrode density and quantity. TacTex overcomes these challenges by employing a multi-layer woven structure that separates conductive weft and warp electrodes with non-conductive yarns. The driving system for TacTex includes a power supply, sensing board, and switch boards to enable spatial and temporal control of electrical stimuli on the textile, while simultaneously monitoring voltage changes. TacTex can stimulate a wide range of haptic effects, including static and dynamic patterns and different sensation qualities, with a resolution of 512×512 and based on linear electrodes spaced as closely as 2mm. We evaluate the performance of the interface with user studies and demonstrate the potential applications of TacTex interfaces in everyday textiles for adding haptic feedback.

CCS CONCEPTS

• **Human-centered computing → Haptic devices**.

KEYWORDS

electrotactile, e-textile, haptic feedback, touch sensing

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1 INTRODUCTION

Textile-based haptic interfaces offer a promising avenue for providing haptic feedback through everyday products such as apparel, furniture, household linen, and vehicle interiors. However, research in this area has been limited, with the majority of research on haptic technologies focusing on mechanical stimulation [10, 11, 55], which hinders the adoption of haptic feedback in many textile products. Electrotactile stimulation involves injecting currents from surface electrodes to stimulate afferent nerve endings underlying the skin, inducing sensations such as touch, vibration, pressure, and spatial-temporal patterns [14, 21]. This motivates the emerging research efforts on developing electrotactile rendering systems with flexible electronic technologies [32]. Though recent study suggests that electrotactile stimulation is a viable method for providing haptic feedback with textiles [13], realizing textile-based electrotactile interfaces is still challenging, particularly in embedding electrodes of high density and quantity into the textile and driving the electrodes for rendering accurate tactile sensations.

As essential elements for electrotactile displays, densely arranged and individually addressed electrodes are critical and those via printed circuit methods have been realized for rigid, flexible, and even stretchable interfaces, but not currently available for textile ones [21–29]. It has been shown that electrotactile interfaces with

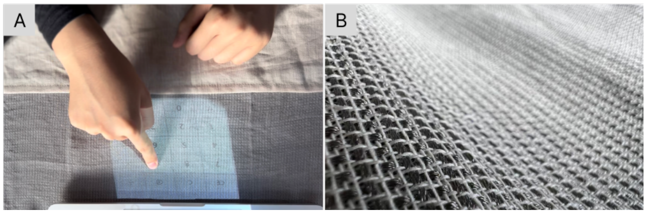


Figure 1: A) TacTex embedded into desk cloth. B) TacTex textile electrodes.

the existing level of electrode quantity (i.e., electrodes with a diameter of 0.89mm arranged on a 7×7 square grid with an inter-electrode spacing of 2.54mm) are capable of stimulating haptic sensations at a spatial resolution compatible with the two-point discrimination thresholds of the fingertip [21]. Built on that, a high-resolution electrotactile interface across a wide area that is well suited to textile applications would require a much larger number of electrodes, and a more capable driving circuit to embed as many switches as necessary to control the electrodes. This is however non-trivial as the switches shall bear high voltages for inducing sufficient current pulses to stimulate the skin and minimizing the switches is challenging. Moreover, adapting textile structure with embedded electrodes in a certain alignment that can elicit various sensations and spatial-temporal patterns requires considerable design effort on function as well as fabrication.

This paper introduces TacTex, a textile-based interface that is capable of providing rich haptic feedback and tracking touch with a resolution of 512×512, utilizing linear electrodes spaced as closely as 2mm(Figure 1). TacTex consists of a dense textile electrode array and a dedicated driving system. The textile electrode array employs a multi-layer woven structure where conducive weft and warp electrodes are separated by non-conductive yarns. Different from commonly used point and concentric electrodes, TacTex utilizes an array of linear electrodes. Besides, our design allows for customization of the electrode size, distance, and side properties as well as visual pattern, and is compatible with commercial textile fabrication process. It is woven in one run, minimizing integration steps and material waste, and is conveniently joined to the driving system. The driving system comprises a power supply, controller, and switches. The power supply regulates and maintains the current output (e.g., 0.5 to 3mA) in changing load conditions, with voltage output up to 350V. The controller operates a good number of switches to control electrical stimuli on the textile spatially and temporally, and simultaneously monitors voltage changes to capture real-time touch events.

We design a broad spectrum of haptic effects, including four types of sensation qualities (e.g., pricking, caressing, tapping, and pressing), ten static patterns (e.g., a thin, vertical line to the left), and ten dynamic patterns (e.g., thin line moving from left to right). Evaluations found that participants can distinguish between the induced sensation qualities, static patterns, and dynamic patterns with acceptable accuracies respectively. We also obtained participants' subjective perceptions of the four sensation qualities. The results indicate that the linear electrode array supports versatile haptic feedback.

Additionally, TacTex is innovative in tracking touch with the same electrodes and pulse amplitude as stimulating haptic effects, simplifying the circuit and control. The TacTex interface has a distinguishable distance threshold of 3mm. To ensure that the touch-tracking stimuli do not disrupt the intended haptic effects, we conducted a second study. This study delved into waveform timing parameters to determine stimuli levels that remain imperceptible to users. Our findings indicate that even with touch-tracking pulse amplitudes matching those of haptic stimulation, reducing the pulse width increases the threshold of scanning frequency at which participants can perceive the stimuli. Consequently, we devised a method that tailors the touch-tracking pulse width and scanning frequency based on these findings, effectively preventing unwanted electrotactile sensations. User evaluations further validated that our sensing techniques do not compromise the haptic effects.

This work contributes to the field of haptic interfaces with textiles in the following ways: i) a textile electrode array design that enables haptic stimulation and touch-tracking with high resolution; ii) a driving system that enables the spatial and temporal control of electrical stimuli while simultaneously monitoring voltage changes with 512×512 resolution; iii) a broad spectrum of haptic effects, including sensation qualities, static patterns, and ten dynamic patterns useful to human-computer interaction; iv) touch-tracking processes and methods used with TacTex interfaces that does not interfere with the haptic stimulation; v) potential applications of TacTex interfaces for adding haptics to everyday textiles.

2 RELATED WORK

TacTex is developed to render high-resolution tactile sensations on textiles. The work is highly related to the recent progress in haptic technologies including tactile surfaces, flexible actuators and electrotactile interfaces. It is also reflecting on the broad interest on interaction design with smart textiles.

2.1 Tactile Surfaces

In recent years, there has been a growing interest in generating tactile effects on touch surfaces used in various electronic devices, including mobile phones, tablets, kiosks, information displays, and home appliances, to name a few [5]. These efforts have led to the development of new applications in user interface design, gaming and entertainment, education, and arts. As touch surfaces evolve to become softer, wearable, and ubiquitous [18, 40, 54, 55], it is necessary to integrate haptic feedback devices seamlessly into daily circumstances.

To address this challenge, recent studies have explored soft actuators as an alternative to rigid haptic actuators, which have a soft and thin form factor, and provide localized feedback to the location of point of interaction. Various types of electrically driven soft haptic devices, including dielectric elastomer actuators (DEAs), electrohydraulic soft actuators (ESAs), ionic polymer-metal composites (IPMCs), and liquid crystal elastomers (LCEs), have been developed and hold the potential for the development of the next generation of haptic feedback devices [4, 20]. These devices offer several advantages, such as lightweight and compact design, untethered activation and control, and distributed and localized actuation, but meanwhile, they often require specialized fabrication processes and non-conventional high-voltage control electronics and are thus limited in commercial availability.

In this context, our work explores another form of soft haptic interfaces that are integrated into textiles. Textile interfaces possess the above-mentioned advantages, develop upon booming e-textile technologies, and are widely and intimately used by humans, potentially bringing haptic feedback to everyday life via a broad range of textile products and surfaces.

2.2 Electrotactile Interfaces

Electrotactile stimulation involves the use of surface electrodes to stimulate afferent nerve endings located in the skin, which generate various sensations, including touch, vibration, pressure, and spatial patterns [14, 21]. Electrode designs commonly used in electrotactile interfaces include circular, square, and concentric electrodes, and electrode arrays with individually connected electrodes that enable different stimulation modes [26]. In our design, we used linear electrodes and found that they can present various sensation qualities, static patterns, and dynamic patterns that are useful for human-computer interactions. This design has the advantage of simplifying electrodes, wirings, and driving circuits.

The driving system of an electrotactile interface is usually complex as it requires high driving voltage and multiple channels. The driving voltage is usually high because it should inject current exceeding the threshold value of skin perception, and skin-electrode interfaces have high impedance. Different techniques have been proposed to lower the driving voltage, including the use of wet electrodes, finger caps and gloves that maintain pressure and moisture of contact between electrodes and the skin [9], and micro-needle electrodes [48]. However, these techniques are not suitable for barehand interaction on textiles, which is the focus of our study. Recently, some studies have proposed new methods to lower the stimulation voltage by using two AC currents of 10kHz but with a 180° phase difference, which reduced the voltage to between 13 and 28 V. In our design, we used electrical stimuli similar to [23], which entails a low overall duty ratio, enabling simultaneous sensing stimulus based on time division multiplexing.

2.3 Textile Interfaces

The HCI community has been investigating the potential of textiles to perform electronic functions, given their widespread and intimate use in everyday life. To this end, textiles have been integrated with various functional materials, enabling them to store data [7], harvest and store power [12], sense user input and everyday objects [1, 2, 34, 36, 38, 39, 42, 43, 50, 52, 53], change colors and display visuals [6, 46], and generate mechanical changes in shape, locomotion, and force [15, 31, 33, 37]. Additionally, textile electrodes have been developed for applications such as biopotential signal monitoring [41, 49] and electrical stimulation to build muscle strength, create or support limb movement, or reduce pain [14]. In this work, we present the first application of textiles for electrotactile stimulation in HCI.

Textile electrodes can be fabricated using different methods, which vary in integration level from low to high [14, 17]. These methods include cutting conductive patches and stitching them onto regular textiles [35, 44], printing, coating, or ironing conductive materials onto textile substrates, embroidering or machine stitching electrodes with conductive yarns [1, 2, 19], and knitting or weaving the textile with embedded electrodes in a single process step. TacTex textile electrode array is woven in one run, minimizing processing steps and waste of raw materials, which becomes increasingly important when fabricating a large number of electrodes. Additionally, our textile electrode array can be easily customized using open-source software, and the drafted designs can be reliably fabricated by weaving professionals and weaving machines widely available in the industry, mitigating the need for domain knowledge, customized looms and software applications to designers [3, 16, 19, 44].

3 TACTEX INTERFACE

TacTex interface (Figure 2) achieves high-resolution electrotactile stimulation and touch tracking by facilitating innovations in textile structure, driving circuits, haptic rendering, and integrated sensing. This section presents the design of TacTex textile weave structures, evaluates a series of representative structure variations, and describes the driving circuit and a convenient technique for connecting a TacTex textile to it.

3.1 Textile Design

Figure 3A shows the design of an example TacTex textile, in which the warp electrodes are separated from each other by non-conductive warp yarns, and the weft electrodes are separated from each other by non-conductive weft yarns. The warp electrodes are separated from the weft electrodes on the top layer by non-conductive weft yarns on the bottom layer, taking advantage of the two-layer structure. The weave structure can be adjusted for variation in the following aspects:

Electrode Sizes and Distances. As shown in Figure 3B, the electrode size can be adjusted by changing the number of conductive yarns in an electrode, and the electrode distance can be adjusted by changing the number of non-conductive yarns between electrodes. A short distance between electrodes can increase electrode density related to the resolution of an electrotactile interface, but increases the chance of short circuits, and this can be mitigated by increasing the number of layers. In each weave unit, the column of weft yarns and the column of warp yarns are the same, so that the warp and weft electrode densities are equal.

Side Properties. In Figure 3A, both warp and weft electrodes can be touched on the top side, while only warp electrodes can be touched on the bottom side. This structure is a simple solution if the top side is interacted with, and the bottom side does not require insulation. In Figure 3C, in a double-side design, both warp and weft electrodes can be touched on both sides, while in an insulating-bottom design, both warp and weft electrodes can be touched on the top side, but neither warp nor weft electrodes can be touched on the bottom side.

Appearance Patterns. As shown in Figure 3D, while keeping conductive yarns the same, the color and the raising and lowering manner of non-conductive yarns can be changed. This creates a series of weave units that share the same electrode structure but

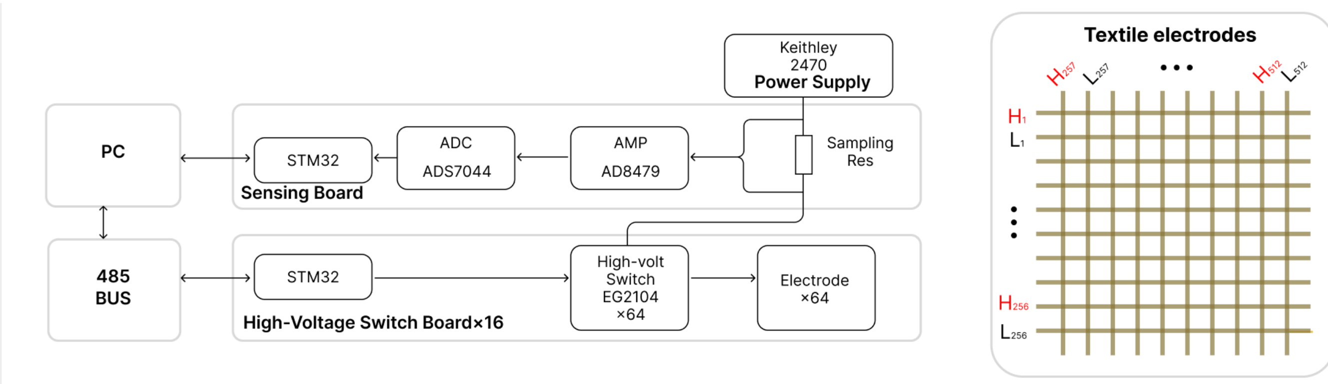


Figure 2: TacTex comprises the power supply, the sensing unit, the switches unit, and the textile electrodes.

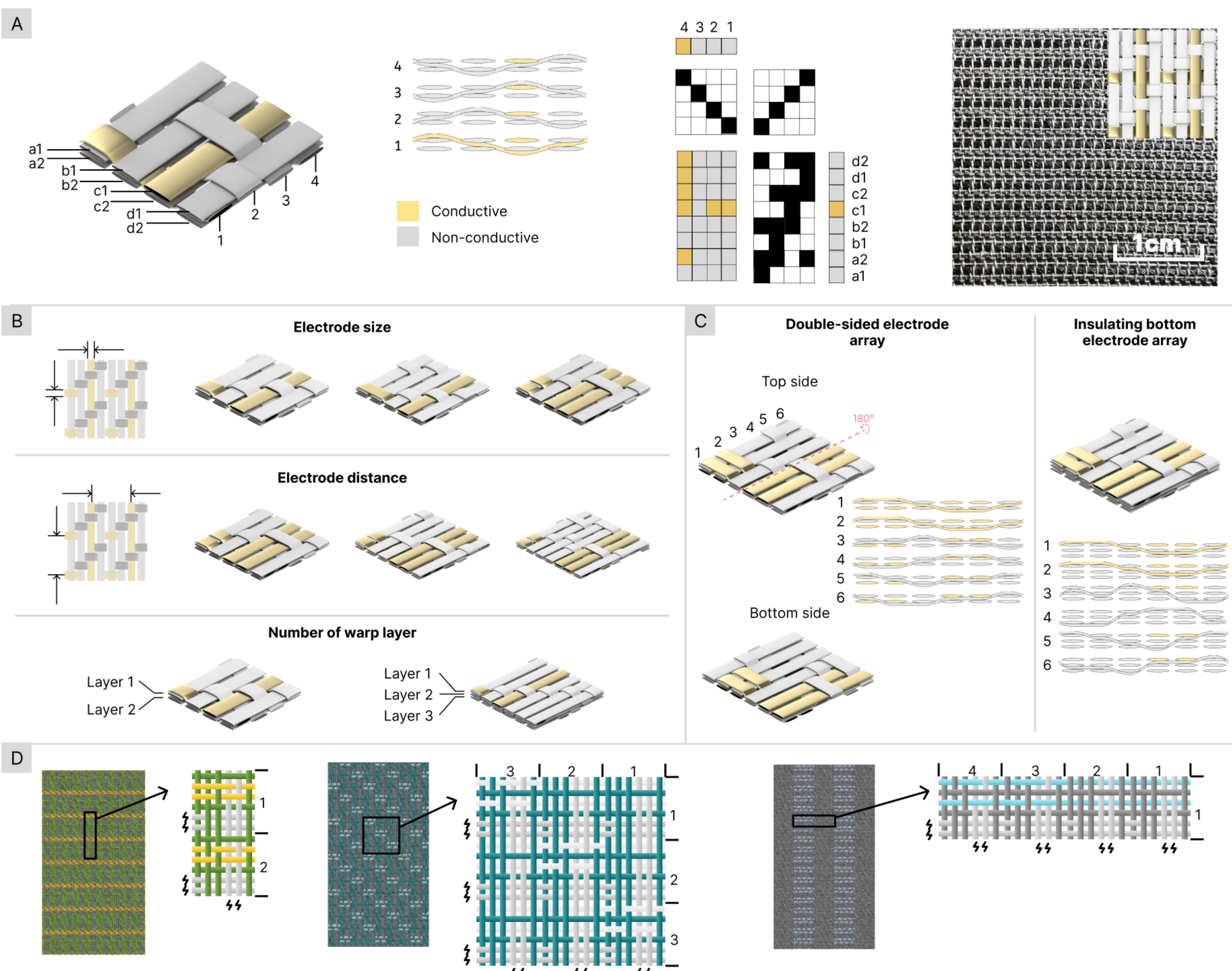


Figure 3: TacTex textile design. A) The unit 3D view and unit cross-section views of an example TacTex weave structure, along with a pattern draft and a photo. B) Structure variations of various electrode sizes, distances, and textile layers. C) Structure variations for textiles with double-side electrodes and insulating-bottom. D) TacTex textiles with customized visual patterns.

appear in different colors, which can be used to compose TacTex interfaces of different patterns.

3.2 Textile Feasibility & Durability Evaluation

The ability of textile structures to maintain electrode constructions under common usage scenarios was evaluated. The evaluated weave structures were fabricated using different yarns and weaving machines, as shown in Table 1. The yarns used to fabricate the samples were commercially available. Kazhtex 70D/3 (consisting of three strands, with each strand having a diameter of 70D before coating) is based on a polyamide 6.6 core with a 99.9% silver coating. After twisting and metallization, the combined strands had a count of 275+-10D. The resistance was less than $500\Omega/m$. The non-conductive yarns were the same as the core of the conductive yarns. Electrodes in the textiles were all spaced at 1mm.

TacTex textiles can be fabricated with conventional 2D weaving machines, which are widely and readily available for 3D fabric production, or 3D weaving machines, which enable more efficient production and result in textiles with better mechanical properties [30]. Specifically, in this study, one 2D weaving machine (i.e., sample rapier loom FYI DW598) and one 3D weaving machine (i.e., rapier loom GA747) were used to fabricate the samples.

The evaluated textile structures were assessed based on their short circuit rate, R, which equals the number of joined points between a warp and weft electrode divided by the total number of warp and weft electrodes. The short circuit rate was measured before and after applying physical deformations that are commonly encountered in usage scenarios, including stretching, shearing, scratching, and bending. Each deformation was applied 1000 times in both the warp and weft directions, using customized and motorized test rigs. In addition, the insulating-bottom design was evaluated for its insulation performance. The results showed that the minimal structure that had the densest electrode and the thinnest layers, based on the materials and fabrication methods used in this study, yielded satisfactory electrical reliability in that no short circuits were identified through deformations.

3.3 Connecting TacTex Textile to Driving Circuit

We present a technique for connecting numerous electrodes in the textile to contact pads on a custom flexible printed cable. This connection is achieved without adding rigid or bulky elements, as shown in Figure 4. It utilizes anisotropic conductive adhesives (ACA) [47], in which the concentration of conductive filler is adjusted so that when the ACA is sandwiched between two contacts stacked on top of each other, it conducts electricity in the vertical (z-) direction, but not in the x-y plane. The method involves the following key steps:

Preparing the textile edges. The edge bands and the inner area of the TacTex textile are woven in the same run but employ different patterns. For example, in the weft direction edges, weft conductive yarn is replaced with non-conductive yarns, and vice versa. Before cutting off the fraying raw edges, a TPU film is applied to the edges on the back side to prevent unraveling.

Customizing the flexible printed cables. One end of the cable is reinforced with a stiffener to facilitate insertion into the PCB, while the other end has contact pads at a pitch compatible with the textile. These cables are manufactured with polyimide and copper.

Assembling the connection. The electrodes on the edges and the contact pads on the FPC are joined and fixed with a bar clamp. Before clamping, an ACA film (3M 9703) is sandwiched between the textile and FPC. Clamping pressure is maintained above 0.10 Mpa for up to 24 hours. As a result, the solidified adhesive maintains compressive stress and establishes an electrical and mechanical interconnection.

3.4 TacTex Driving Unit

A driving circuit designed for 512×512 electrodes has been developed (Figure 5). This circuit comprises an adjustable high-voltage constant-current power supply, a sensing board, and 16 sets of controllers paired with tri-state switches. Each controller is built around the STM32F207 microcontroller. Communication between the controller and the PC, as well as inter-controller communication, is facilitated through RS485. This communication protocol, which employs differential signal transmission, is adept at mitigating interference from high-voltage pulse waveforms. As directed by the controller, a switch—comprising components EG2104 and BSS127S (refer to Figure 5B)—can connect an electrode to either the ground, a high voltage, or place it in a high impedance state. The controllers control switches to adjust stimulus location and waveform timing. The sensing board compares voltages measured from the sampling resistor to a reference value; if the values are the same, the activated pair of a High-type electrode and a Low-type electrode is not touched, and vice versa.

Latency of the driving circuit is contingent upon the STM32F207's clock frequency (72MHz) and the inherent analog characteristics of the switch component. Through testing, we have ascertained that the latency between the issuance of a control signal and achieving the desired output voltage state is no more than $3\mu s$. The current loss observed in the switches remains below 1% of the predetermined current value. Given that the electrical stimuli operate as a high-frequency AC signal, it is prone to generating crosstalk in neighboring circuits. Complete eradicating crosstalk remains challenging. However, it is attenuated in our design that separates the electrodes into high electrodes that are connected to either the high voltage or high impedance and low electrodes that are connected to either the ground or high impedance. Our measurements indicate that the peak amplitude of any interference waveform consistently stays below 5V, ensuring it does not notably impede touch tracking.

4 HAPTIC STIMULATION WITH TACTEX

This section introduces haptic effects that a TacTex interface can stimulate and an evaluation of simulation performance with users.

4.1 Haptic Effects Supported by TacTex

A TacTex interface stimulates various sensations and spatial-temporal patterns by adjusting the spatial parameters of electrodes and the timing parameters of electrical stimuli. The electrodes' spatial parameters include orientation, position, and distance (see Figure 6A). TacTex uniquely activates a pair of parallel anode and cathode electrodes at a time for achieving localized tactile sensations, essential for composing spatial-temporal patterns. This activation method

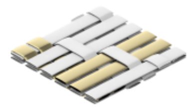
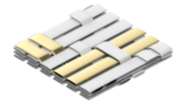
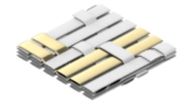
Structure	1			2			3			4						5		
																		
Insulating	Nylon	PE	Nylon	Nylon	PE	Nylon	Nylon	PE	Nylon	Nylon		PE		Nylon		Nylon	PE	Nylon
Conductive	Silver	Steel	Silver	Silver	Steel	Silver	Silver	Steel	Silver	Silver		Steel		Silver		Silver	Steel	Silver
Machine	2D	2D	3D	2D	2D	3D	2D	2D	3D	2D		2D		3D		2D	2D	3D
										Top	Btm	Top	Btm	Top	Btm			
Initial R	.07%	.03%	0	.03%	.04%	0	0	0	0	.04%	.04%	.01%	0	0	0	0	0	0
Stretch R	.07%	.03%	0	.03%	.03%	0	0	0	0	.04%	.04%	.01%	0	0	0	0	0	0
Shear R	.07%	.03%	0	.03%	.05%	0	0	0	0	.04%	.04%	.01%	0	0	0	0	0	0
Bend R	.07%	.03%	0	.03%	.03%	0	0	0	0	.04%	.04%	.01%	0	0	0	0	0	0
Scratch R	.09%	.03%	.03%	.03%	.03%	0	0	0	0	.04%	.05%	.01%	0	.01%	0	.01%	0	0

Table 1: Evaluation of the electrical reliability of TacTex textiles. The short-circuit rates, R, are presented for TacTex textiles across various weave patterns, materials, loom types, and deformations. The definition of R is provided within the text.

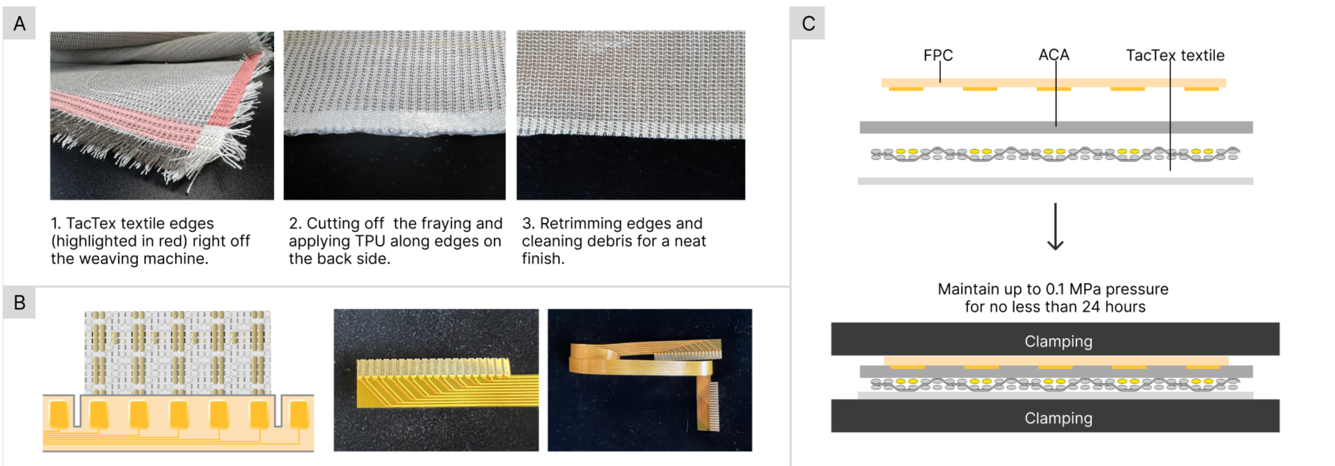


Figure 4: Technique to connect TacTex textile to a circuit board. A) Preparing the textile edges. B) Customizing flexible printed cables. C) Assembling the textile and flexible printed cables.

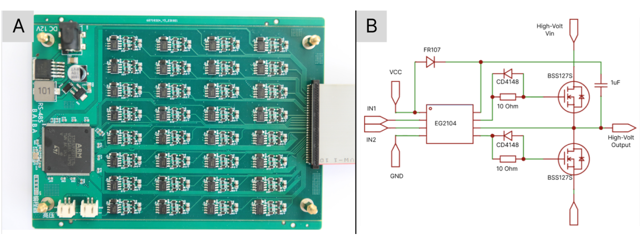


Figure 5: A, Photo of a piece of switches circuit board containing 64 switches. B, switch circuit.

emerged from our early design iterations. We also explored two other activation methods that proved less effective. The first was activating a pair of perpendicular anode and a cathode at a time. However, it resulted in a sensation spreading along the electrode lines rather than concentrating at the intersection point. The second was activating an anode and multiple cathodes perpendicular to the anode. While this method produced a local sensation along the thin anode electrode when one firmly touched the intersection, varying contact situations often meant only a small area of the cathode was touched. This inconsistency made sensation delivery to the anode line unreliable, leading to its rejection.

Each pair of electrodes carries an electrical waveform. The electrical waveform timing parameters are shown in Figure 6B-1. The output waveform consists of pulses grouped into bursts, and it is defined by the pulse width (PW), pulse period (PP), pulse number (PN), burst period (BP). In stimuli involving multiple electrode pairs, the waveforms across different electrode pairs share the same shape but are staggered on the time axis, as shown in Figure 6 B-2.The electrode pair number is referred to as channel number (CN), and the temporal displacement is inter-channel period (ICP). To ensure the integrity of the burst structure, the following numerical constraints must be maintained: $PW < PP < ICP$, $ICP \times CN < PP$, and $ICP \times CN \times PN < BP$. Electrotactile pixels activated within the same burst period are perceived as activated together by the user. Our choice to use three separated pulses per burst instead of a longer successive pulse on one channel is based on literature [22, 25]. First, a pulse width longer than 200 μs has a higher risk of eliciting pain and shock sensations. Second, humans tend to perceive pulses within 15ms on the same stimulating location as a single stimulation. The current intensity is constant for an individual and is calculated from their detection threshold and pain

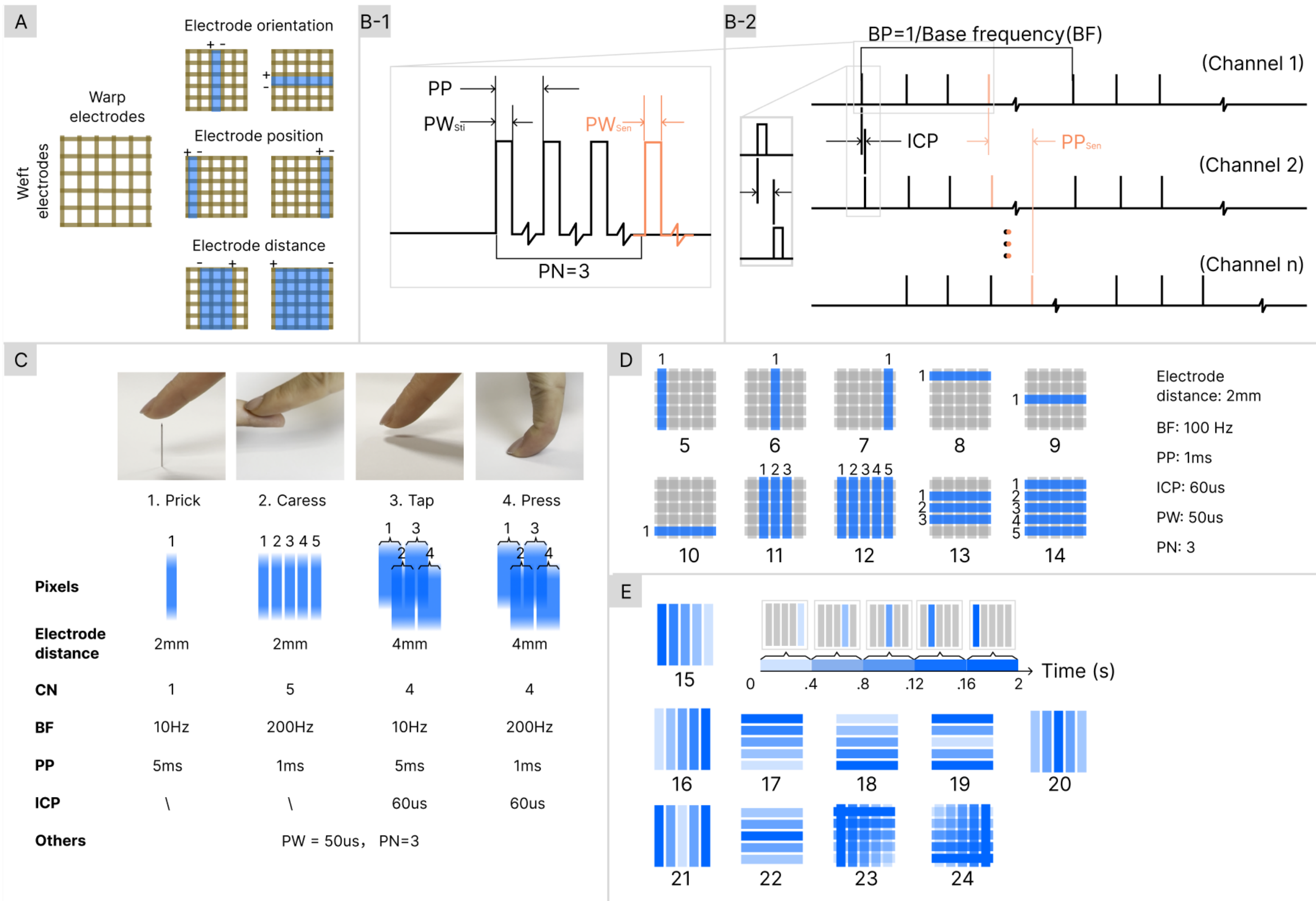


Figure 6: Haptic stimulation with TacTex interface. A) An electrotactile pixel varies with electrode orientation, position, and distance. B) The electrical stimulus waveform template and timing parameters. C) Four sensation qualities and their electrode spatial parameters and electrical stimulus timing parameters. It is worth noting that the photos are only meant to illustrate the feeling, not the shape of sensations. The numbers displayed above the pixels represent the channel identifier numbers. D) Ten static patterns. E) Ten dynamic patterns; pixels in the same shade are stimulated within the same frame, and pixels in darker shades are stimulated later.

threhold, ranging from 0.5 to 3mA from the user experiment calibration round.

Sensation qualities. The interface can stimulate four different sensation qualities, including pricking, caressing, tapping, and pressing, as shown in Figure 6C. These qualities are achieved by adjusting pixel properties and burst parameters. Specifically, *Pricking* produces a discrete, sharp sensation that affects a focused area of the skin. The sensation is shallow, affecting only the superficial layers of the skin. *Caressing* produces a continuous, blurry sensation that is also shallow. *Tapping* produces a discrete, blurry sensation that is deep, penetrating into the skin. *Pressing* produces a continuous, blurry sensation that is also deep.

Static and dynamic spatial patterns. TacTex can display various static spatial patterns composed of warp and weft pixels, as illustrated in Figure 6D. In patterns involving multiple pixels, the waveforms across these channels are identical in shape but temporally displaced, as depicted in 6B-2. Within each pulse period, all electrode pairs are activated once. TacTex can display dynamic patterns by sequentially updating static patterns over time frames, as shown in Figure 6E. We present ten such dynamic patterns here, each repeating every 2 seconds. The number of frames within this 2-second period is indicated by the number of different shades. The duration of each frame is calculated by dividing 2 seconds by the number of frames. In each frame, pixels are activated in the same manner as in a static pattern.

4.2 Exp-1: User Evaluation on Electrotactile Sensations

This study evaluates the performance of the TacTex interface in eliciting four sensation qualities and displaying ten different static tactile patterns and ten tactile animations composed of static patterns and assesses the level of pain caused by the electrodes in electrotactile stimulation. User experiment setting is shown in Figure 7.

4.2.1 *Participants and Procedure.*

Twelve healthy adults (6 females, mean age: 24.5 years, SD: 3.68 years) participated in this experiment after providing informed consent. None of the participants had prior experience with electrotactile stimulation. The study was approved by the ethics committee of a local university, and the participants were allowed to withdraw from the study if they felt any uncomfortable sensations.

Before the commencement of each experimental session, the participants were instructed to wash their hands to remove any debris (e.g., dirt or hand lotion) that might interfere with electrotactile sensation. Following familiarization with the nature of the electrotactile stimulation and the experimental apparatus, the participants underwent 6 calibration trials to determine their sensation threshold (I_s) and 6 more trials to obtain their maximum level without discomfort (I_m). The current intensity at $I_t = I_s + 0.8(I_m - I_s)$ was used in the subsequent formal study. In practice trials, the participants performed four trials of each of the 24 pattern exposures, during which they viewed the patterns to associate their shapes with their corresponding sensory experiences. Following a brief waiting period to allow recovery from any possible sensory adaptation caused by the practice trials, the participants were subjected to experimental trials.

There were three tests. In the first test, the participants were required to select the sensations they perceived from pricking, caressing, tapping, or pressing. In the second test, the participants were asked to select the sensations they perceived from static patterns 4, 5, 6, 7, 8, 9, 11, 12, 14, and 15. In the third test, the participants were asked to select the sensations they perceived from dynamic patterns 16, 17, 18, 19, 20, 21, 22, 23, 24, and 25. Within a test, each sensation, static pattern, and dynamic pattern was presented six times in a random order, sampled without replacement. At the onset of the stimulus, the computer simultaneously presented the choices, and the participants had as much time as they required to choose. At the end of the study, the participants were asked to fill out a unidimensional pain questionnaire in the form of a numeric rating scale (NRS), whereby a segmented scale was used, where 0 denotes 'no pain' and 10 denotes 'pain as bad as could be'. It is worth noting that in an experimental trial, the textile interface consistently provides stimuli without detecting the specific location or timing of participant contact. A potential concern might arise regarding differentiating between Pressure and Tap when a participant briefly touches and then releases. To address this, it is important to understand that typically, the action of touching and releasing occurs over approximately 100ms, whereas a single Tap stimulus, characterized as a group of pulses, lasts around 10.05ms ($PP \times 2 + PW$). Therefore, even with rapid touch-and-release actions by the participant, it is theoretically possible to distinguish between Tap and Pressure.

In the final stage of this experiment, participants were invited to engage in an interview session. Here, they had the freedom to interact with the four sensation qualities. Participants were then encouraged to articulate their perceptions of these sensations using their own vocabulary and to draw comparisons among them.

4.2.2 *Results Analysis.*

The performance of the interface in displaying sensations of different qualities, static patterns, and dynamic patterns was measured by the accuracy of the participants' perception of the stimuli. We calculated the accuracy of sensation qualities, static patterns, and dynamic patterns by averaging the results obtained from all the participants. Figure 8 displays the stimulus-perception (S–R) matrices. Additionally, we computed the balanced accuracy of each class in each test. The results indicate that the accuracy of sensation qualities was 0.7805. The balanced accuracy of sensation tapping, pricking, pressing, and caressing was 0.8911, 0.8586, 0.8949, and 0.7706, respectively. The accuracy of static patterns was 0.8792. The balanced accuracy of patterns 5, 6, 7, 8, 9, 10, 11, 12, 13, and 14 was 0.9831, 0.9610, 0.9784, 0.9885, 0.954, 0.9915, 0.8742, 0.8392, 0.8541, and 0.8899, respectively. The accuracy of dynamic patterns was 0.7492. The balanced accuracy of patterns 15, 16, 17, 18, 19, 20, 21, 22, 23, and 24 was 0.9160, 0.9025, 0.8638, 0.8943, 0.9097, 0.8944, 0.8767, 0.8857, 0.7690, 0.7903. The average rating of electrode-induced pain was 2.75, and the standard deviation was 1.60.

All of the participants identified pricking and tapping as discrete sensations, while caressing and pressing as continuous. All noted pricking stimulated a fine line area on the skin, in contrast to the larger areas affected by other sensations. Pressing was deemed more intense than other sensations by five participants (P1, P2, P5, P7). Electrotactile sensations were generally described as more buzzing compared to actual pricking, caressing, tapping, or pressing. Pricking was described as weak (P1), itchy (P1, P4), and less sharp or painful than anticipated (P1 and P7). Caressing resembled "being brushed by a toothbrush" (P2), felt itchy (P4), numb (P5), or "tingly" (P10). Tapping was likened to lightly and quickly hitting a rigid object (P1, P4, P11, P12), and also described as pulsing (P2) or vibrational (P3, P7). Pressing was characterized as "buzzing" (P1, P3, P4, P6, P8, P11), "numb" (P5), "tingly" (P10), or like "being squeezed" (P12).

5 TOUCH-TRACKING WITH TACTEX

This section presents TacTex's method to capture data for touch-tracking. It also details a series of user experiments, specifically focusing on examining the electrical parameters necessary to ensure that the sensing signals remain imperceptible to users. Additionally, it verifies, based on the results of these experiments, that the touch-sensing methods do not impede the interface's haptic feedback.

5.1 Touch-tracking method

TacTex performs touch-tracking using the same hardware as stimulation, including the power source, switches, and electrodes, based on time division multiplexing. TacTex is capable of detecting whether an activated pair of H-type and L-type electrodes has been touched via the sensing board. As shown in Figure 9 A-1, TacTex confirms touch in an element area by that both the warp and weft electrode pairs signal a state change. In this way, TacTex affords the ability to precisely depict the touched area over the whole textile surface. It is worth noting that it is not viable to use a pair of perpendicular anode and cathode in traditional design to tell whether their intersection is touched, as a state change in such case could be a touch

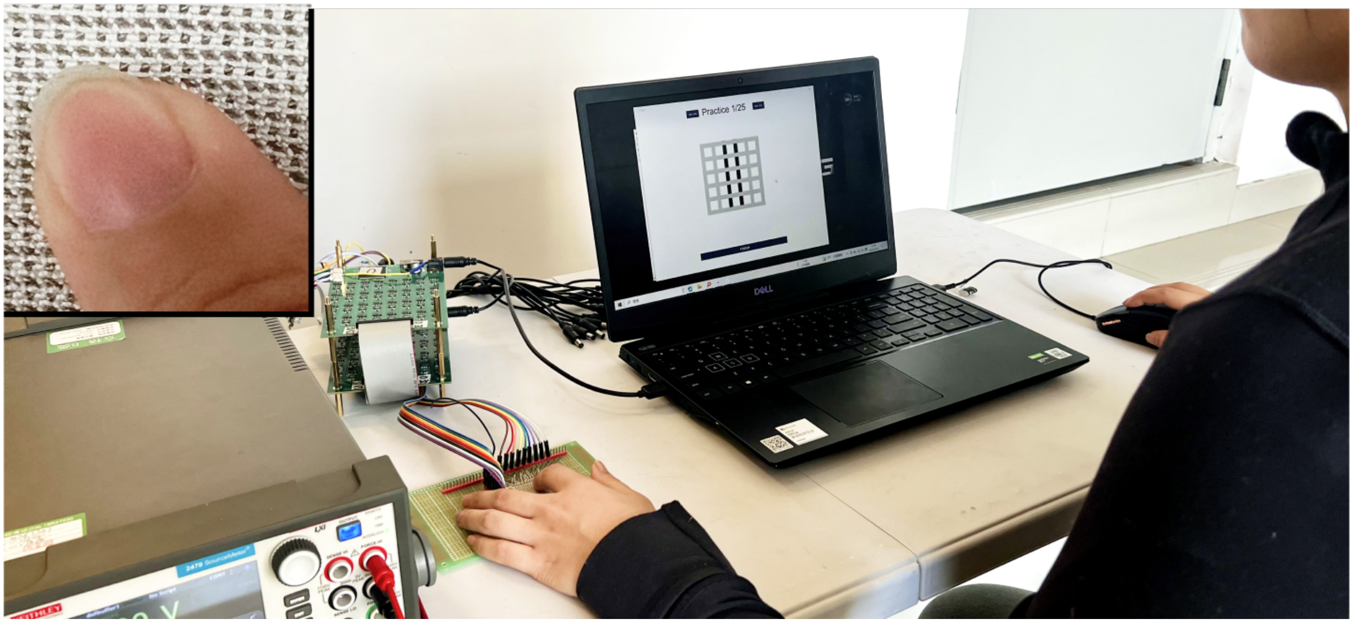


Figure 7: System testing setting. The image on the top left corner shows the textile electrodes.

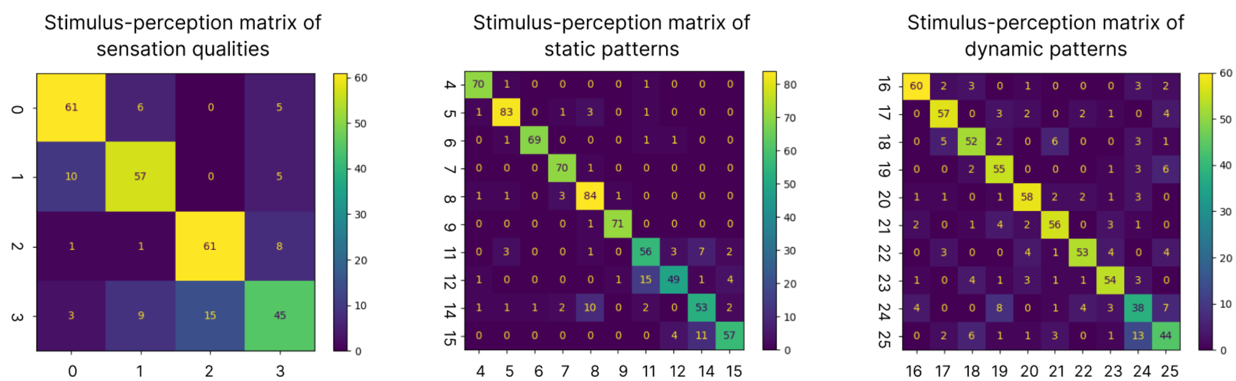


Figure 8: Stimulus-perception matrixes of stimulated patterns and perceived patterns in Exp-1: User Evaluation on Electrotactile Sensations.

at the intersection or a touch remote from the intersection linking the electrodes (Figure 9 A-2).

While TacTex confirms touch in an element area with two times of activation, we have developed various scanning methods, balancing in spatial ambiguity and time cost (Figures 9 B). And we propose two touch-tracking workflows that call among the scanning methods according to conditions to reach precise result at minimal cost of scanning times. They are optimized for simple (e.g., single-finger) and complex (involving multiple fingers/body parts) interactions, shown in Figures 9 C-1 and C-2, respectively. The four scanning techniques include:

(1) **Area scanning** activates all of the electrodes and detects whether the whole textile has been touched.
(2) **Line binary scanning** is performed separately on the lists of warp pairs and weft pairs. The technique begins by checking whether the middle pair of a list has been touched. If it has not, all pairs in the first half of the list are activated to identify the touched half and the middle pair of the touched half is checked until a touched warp pair is found. Line binary scanning yields one of the touched warp pairs and weft pairs.
(3) **Line sequential scanning** is employed to check electrode pairs within a range one by one. This technique yields all the touched warp pairs and weft pairs, i.e., one or more rectangular touched areas.
(4) **Point sequential scanning** is employed to check the intersection point of warp pairs and weft pairs within a range one by one. This technique activates the warp pair and then

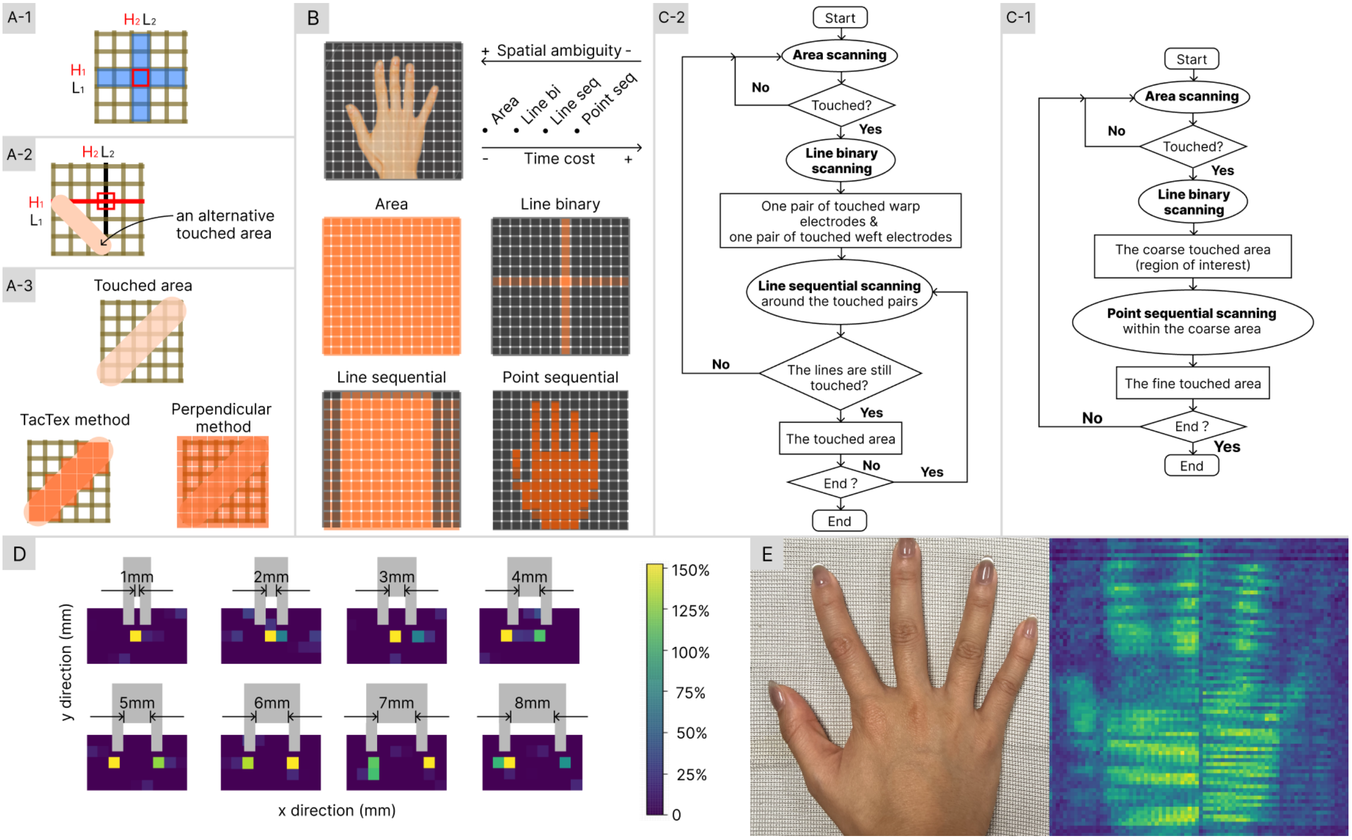


Figure 9: Touching-tracking process and scanning methods. A-1) TacTex touch-tracking principle. TacTex detects whether the intersection area (red stroked) is touched by first activating the H1 and L1 electrode pair, followed by the H2 and L2 pair. If both signal a state change, then it implies that the area must be touched. A-2) Ambiguity in the state change signal from activating a pair of perpendicular electrodes. A state change signaled by activating H1 and L2 does not conclusively indicate a touch in the red stroked area. This ambiguity arises because other areas, such as the pink region, can cause a similar signal. This region, although distant from the H1 and L2 intersection, still connects the two. A-3) The diagrams illustrate the resulted state change mappings of a touched area. B) TacTex data capture methods. C-1)D) Two-point discrimination study of the TacTex interface. Top: Illustrations of differently spaced tips used in the experiment. Response heatmaps under the touch applied through the tips. E) Left: The plam placed over the TacTex interface. Right: Heatmap visualization of raw current of the palm over the TacTex interface.

the weft pair to check one interaction point. The result is all of the touched interaction points.

(5) **Resolution adjustment** is used in line sequential scanning and point sequential scanning to check multiple adjacent electrode pairs together. This adjustment decreases the resolution but also saves the checking times required to scan the entire textile.

As shown in Figure 6B, sensing pulses are incorporated within non-active BPs when there is no stimulating pulse in any pixel. The sensing flow pauses and resumes according to designed stimulating pulses. The whole sensing flow may span across several BPs.

The spatial resolution of the TacTex in touch-tracking was investigated by a two-point discrimination study in Figure 9 D. The study used tin-coated fixture, each with a cross-section of $2 \times 2mm^2$, and intertip distances varied from 1 to 8 mm, with steps of 1 mm. The force exerted by the fixture on the textile was consistently kept at 30 gf. The tips were indiscernible at spacings of 1 and 2 mm but became distinguishable at spacings of 3 mm and above.

5.2 User Experiments in Touch Tracking

To address two main human-centered issues and ensure that touch-tracking pulses do not interfere with the desired electrotactile sensations, we consider the following and conducted three user experiments that determined key parameters like imperceptible interval and frequency in relation to pulse width.

Ensuring that sensing pulses inserted into stimulating pulses are imperceptible to users. Inserting sensing pulses into stimulating pulses can cause pauses, and as pause time increases, users may notice and disrupt the designed electrotactile effects.

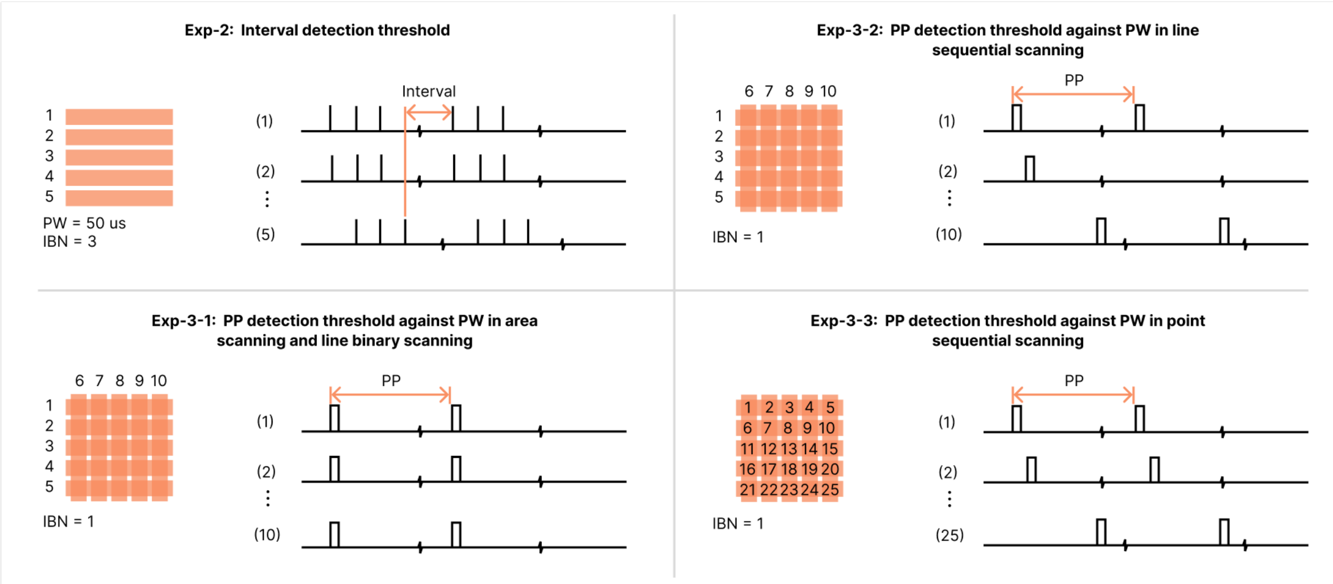


Figure 10: Electrical stimuli used in Exp-2 and Exp-3.

Therefore, we conducted user experiments to determine the detection threshold of pause time caused by sensing pulses.

Ensuring that sensing pulses are imperceptible to users. The amplitude of the sensing pulse is the same as the stimulating pulse amplitude for an individual, and the sensing pulse width is the minimum pulse width provided by the driving circuit. Although the sensing pulse width is short, as the frequency increases, users may become aware of the sensing pulses. Hence, we conducted user experiments to determine the detection threshold of the frequency of sensing pulses.

Three user experiments were conducted. Exp-2 examined the detection threshold of interval duration in continuous haptic effects. Exp-3 and Exp-4 examined the detection threshold of pulse period (PP) against pulse width (PW) for various scanning methods, and evaluated the disturbance caused by touch-tracking to haptic stimulation, respectively.

5.2.1 Participants. A new group of eight healthy adults (3 females; mean age: 25.75 years, SD: 5.23 years) participated in the experiments after providing informed consent. None had previous experience with electrotactile simulation. The ethics protocol and the experiment environment were the same with the previous study.

5.2.2 Exp-2: Interval Detection Thresholds. Exp-2 aimed to determine the sensation threshold of interval duration in continuous haptic effects. The stimuli used in this experiment are shown in Figure 10. Five pixels were repeatedly scanned using PW = 50us and PP = 60us, and a current of I-t was maintained for each participant. An interval was inserted between bursts, and the threshold was measured using the staircase method of classical psychophysics [8]. In this method, a sequence of stimuli was presented, in which the interval duration was increased or decreased in steps of 1ms. The participants were asked to report whether they perceived the stimulus as discrete or continuous. The staircase direction was reversed from ascending to descending or vice versa, and the interval duration value was recorded whenever the subject's response changed. The staircase method was repeated to obtain ten transition interval duration values, and the threshold was calculated by averaging these values. The participants took each trial for 5s and had a 10s break between each trial.

The results showed that the average threshold was 26.17ms, with a standard deviation of 11.2ms. These findings suggest that there is considerable individual variation in the ability to perceive differences in interval duration, but the overall threshold falls within a relatively narrow range.

5.2.3 Exp-3: PP Detection Threshold against PW. Exp-3 investigated the sensation threshold of the base frequency (1/PP) against PW for the four scanning methods: area scanning, line binary scanning, line sequential scanning, and point sequential scanning. To simulate the stimuli received by a user's index finger in the four scanning methods, we designed three stimuli (shown in Figure 10).

Area scanning and line binary scanning. Per cycle of line binary scanning, a finger, at worst, receives $x = 2\log_2 m + 2\log_2 n$ (m and n are the numbers of warp pairs and weft pairs, respectively) times of area scanning. The sensation threshold of the base frequency of actual area scanning stimuli should equal the stimuli shown in Figure 10. The sensation threshold of the base frequency of actual line binary scanning stimuli should be above 1/x of the sensation threshold of the base frequency of the sensation threshold of the stimuli shown in Figure 10.

Line sequential scanning. In a cycle of line sequential scanning, a finger receives warp pair scanning pulses and, after an interval depending on the scanning range and the finger position, receives weft scanning pulses. The sensation threshold of the base frequency of actual line sequential scanning stimuli should be above the stimuli shown in Figure 10.

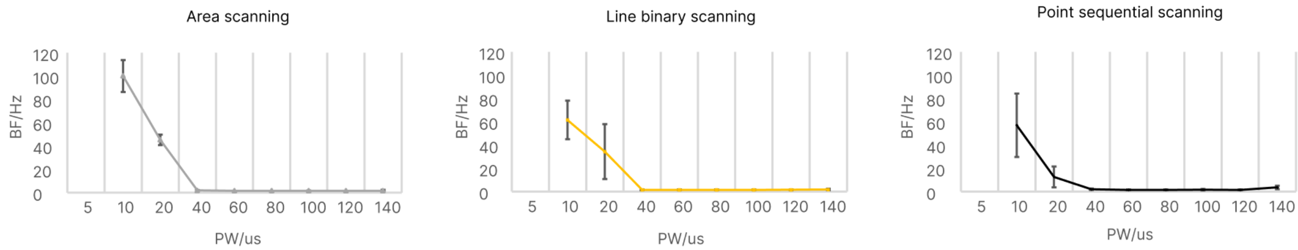


Figure 11: Results of Exp-3 on PP Detection Threshold against PW with different scanning approaches.

Point sequential scanning. In a cycle of point sequential scanning, a finger receives scanning pulses for points on the first warp pair, after an interval depending on the scanning range and the finger position, receives scanning pulses for points on the next warp pair, until all warp pairs on the finger have been scanned. The sensation threshold of the base frequency of actual point sequential scanning stimuli should be above the stimuli shown in Figure 10.

We tested the sensation thresholds of the base frequency when PW was set to 5, 10, 20, 40, 60, 80, 100, 120, and 140 for the three stimuli shown in Figure 10. The current was maintained at I-t for all the participants. We used the staircase method [8] to measure the threshold frequencies. The participants were asked to indicate the presence or absence of the stimulus by choosing yes or no, and we obtained ten threshold values. The threshold was calculated as the average of the ten transition frequencies. The PW and scanning methods were counterbalanced.

The results are shown in Figure 11. Across various scanning methods, there is a discernible trend whereby the threshold frequency decreases as pulse width (PW) increases within certain ranges. The participants are unable to perceive stimuli even at the highest frequency of 250kHz provided by the system when the PW falls below this range. Conversely, when PW exceeds the range, the participants can perceive stimuli even when the frequency is as low as 1Hz.

5.2.4 *Exp-4: Effects of Touch-tracking Stimuli on Haptic Stimulation.*

This experiment aimed to evaluate the level of difference between designed haptic effects and actual effects delivered by the TacTex interface when it also performs touch tracking. The evaluation was performed with respect to the four haptic qualities, ten static patterns, and ten dynamic patterns. In each trial, the participants were presented with a haptic effect on their index finger, and then asked to place the index finger on a random location on the textile performing multitouch-tracking process to receive the same effect. The participants were then asked to report whether the haptic effects in the two conditions were the same by choosing yes or no. Based on the results of experiments 1 and 2, the touch-tracking stimulus timing parameters were set as follows: 1) the pulse width (PW) of the four scanning methods was set to $5\mu s$, which is about the shortest PW supported by our system; 2) the pulse period (PP) of the four scanning methods was set to $10\mu s$, which is about the shortest PP supported by our system. Within an experiment, each sensation, static pattern, and dynamic pattern was presented six times in a random order, sampled without replacement.

All of the responses from the participants were no. The result showed that the actual haptic effects provided by the TacTex interface when it performs touch-tracking have no perceivable difference from the designed haptic effects.

6 EXAMPLE APPLICATIONS

TacTex can be easily integrated into various living circumstances and facilitates ubiquitous haptic interactions. We developed four prototypes leveraging TacTex's tactile sensing and actuating capabilities, tested them within our research team, and envisaged four potential applications.

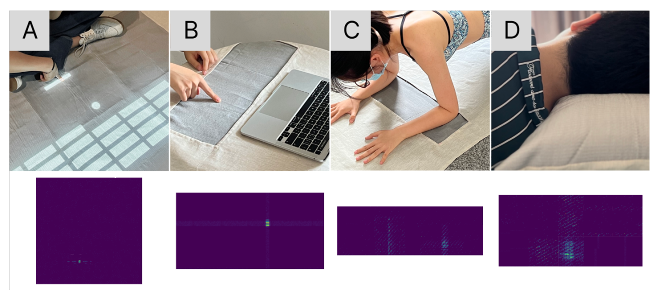


Figure 12: Example applications with visualizations of raw current data captured over the whole textile. A) Large-size TacTex interface with projected visual content. B) TacTex interface integrated into desk cloth. Example applications in embedded haptic display. C) TacTex interface embedded in a yoga pad. D) TacTex interface integrated into a pillow.

6.1 Projector-based Interactive Surface

This prototype utilizes a TacTex system with a 512×512 electrode textile (2mm spacing) and incorporates a projector to display visual content on the textile (as shown in Figure 12A). A ping-pong game was developed for this system, allowing users to interact with the textile similarly to a touchscreen. The prototype enriches the gaming experience with various haptic effects, as detailed in Section 4.1. We envision TacTex enhancing projector-based interactive surfaces commonly used in gaming and education, which transform everyday surfaces like tables, walls, floors, and clothing into interactive displays. Unlike these traditional solutions that typically require additional hardware for input detection and lack haptic feedback, TacTex provides a scalable tactile sensing and actuating solution for various surface sizes.

6.2 Desk cloth

The desk cloth prototype (Figure 12B) utilizes a TacTex system configured with 128×256 electrode textile (2mm spacing), also paired with a projector (Figure 12B). We developed a virtual numeric keypad. Touching the edges of a key triggers static pattern effects to simulate the key edges, while touching the center of a key activates a brief Tap effect. The envisioned TacTex desk cloth could provide more virtual tactile inputs, adaptive to the context of interaction. It could also serve as a tactile alarm for napping users. This desk cloth allows for tactile-feedback inputs and tactile notifications without occupying additional space.

6.3 Yoga Mat

This yoga mat prototype (Figure 12C) is embedded with a TacTex interface with 128×384 electrodes (2mm spacing). The mat tracks a player's touch across the TacTex textile, enabling the use of a PC to alter the haptic feedback provided. This feedback can guide the player in movements such as rotating an arm. Future TacTex-based yoga mats, coupled with smart programs that interpret posture and movement, could offer customized tactile guidance to enhance yoga practice.

6.4 Pillow Cover

The pillow cover prototype (Figure 12D) incorporates a TacTex interface with 192×384 electrodes (2mm spacing). This prototype is designed to deliver a range of preset haptic effects to the neck or cheek of a user lying on it. We envision that, while watching videos, the pillow can enhance the visual and auditory experience for a more immersive sensation. Additionally, when a user is speaking to someone remotely, the pillow can transmit a physical touch from the remote one, such as caress sensations.

7 DISCUSSION

With the development of TacTex, we present the first large-scale textile-based electrotactile interface with integrated high-resolution haptic stimulating and touching sensing. It provides a viable solution to incorporate haptic rendering into apparel and everyday fabrics which have become prominent venues for ubiquitous computing. Our work systematically and empirically investigated key points regarding the novel electrode array design and sensing/stimulating signals, and optimized the design of driving circuits. These are critical and challenging, yet the work could constitute the foundation for the future development and deployment of textile-based electrotactile interfaces.

7.1 Linear Electrode Array Design as a Feasible Method to Display Various Sensations

In this work, we introduce a novel electrode array design for electrotactile stimulation, which consists of warp and weft electrodes. Compared to conventional electrode arrays of point electrodes or concentric electrode pairs, the TacTex electrode array supports competitive versatility. A TacTex electrotactile pixel can be varied by adjusting the pair of parallel electrodes in their orientation, position, and distance. Activating electrotactile pixels with electrical stimuli that can be adjusted in various timing parameters, TacTex interfaces support sensation qualities, and static and dynamic patterns.

Although the linear electrode array does not offer the detailed patterns that a point electrode array can, it remains an optimal solution as the intricate patterns of the point-based system would take longer for both the system to display and for users to recognize. Such delays are not ideal in many human-computer interaction scenarios, especially those large-scale ones as proposed in our work. That said, TacTex does have its limitations when compared to point-based electrodes. Firstly, the larger size of line electrodes compared to point electrodes might result in less consistent electrotactile sensation intensity. Under dynamic contact conditions, the skin-electrode impedance varies. Smaller electrodes can limit this range of change, thereby making electrotactile stimulation more stable. Secondly, in scenarios involving multiple touch areas or users, stimulating one body part might inadvertently affect another. For instance, as illustrated in Figure 12A, if multiple users are playing a game and we aim to stimulate one participant's finger, we might unintentionally stimulate another participant's finger if they touch the activated line electrodes. To address these issues, we could consider segmenting the electrotactile interface to drive or employing algorithms to interpret touch conditions to adjust stimulation methods to prevent such conflicts.

7.2 Towards Large-Scale Tactile Interfaces

A clear benefit of the TacTex electrode array design is that it significantly simplifies high-resolution tactile interfaces. With traditional designs, an electrode array reaching $m \times n$ resolution requires $m \times n$ electrodes or electrode pairs, and each electrode is accompanied by a switch. Our design reduces the number to $m + n$, and the simplification becomes more significant when the resolution is higher.

Compared to previous fabrication methods, TacTex electrode arrays are much cheaper to fabricate. Once the weaving machine is set up, it can weave very long fabric at a low cost increase. The conductive yarns and weaving machines are readily available. The fabrication process requires fewer steps, and the electrode array size can be much larger than printed circuit methods, thanks to the scale effect. The fabricated textile, with specially designed edges, can be easily connected to external circuits via customized flexible adaptors. However, we note that given the yarns and woven textile nature, the electrode array may be more subject to wear than those of conventional circuit board designs. Nonetheless, there are still questions to be studied. For example, in real-world applications, clothes are susceptible to moisture and scratches by sharp objects. However, since the textile industry is one of the largest and most developed industries, it is possible to solve these problems by borrowing from a considerable amount of technology on high-performance yarns and textiles, such as moisture-wicking and high-strength yarns and fabrics.

We also note that another obstacle to high-resolution electrotactile interfaces is the driving circuit; although our design has reduced the number of needed electrodes, the number is still considerable. The emergence of suitable integrated chips could greatly help bring high-resolution electrotactile interfaces to the market.

7.3 Integrated Haptic Stimulation and Touch-tracking

Previously proposed electrotactile interfaces have typically focused on providing haptic feedback through an electrode array without using the same hardware for touch tracking, which is an essential function of haptic interfaces. However, TacTex utilizes the same electrode array for both haptic feedback and touch tracking, which has several benefits. By eliminating the need for additional components for touch tracking, TacTex reduces the overall complexity and bulkiness of the textile interface, making it more user-friendly and cost-effective. However, integrating touch tracking and haptic feedback in the same hardware can be a non-trivial task. TacTex uses time-division multiplexing to insert the sensation pulses into the stimulating waveforms while ensuring that the sensing pulses do not interfere with the haptic stimulation. This requires careful design and implementation of the controller and switches to enable precise temporal control of the electrical stimuli on the textile, while simultaneously monitoring voltage changes. The ability to combine touch tracking and haptic feedback in the same hardware opens up new possibilities for the design and application of haptic interfaces. For example, it can allow for more natural and intuitive interaction between users and electronic devices, enabling a more seamless and immersive experience. However, the challenges of integrating touch tracking and haptic feedback also highlight the need for continued research and development in this field to overcome technical limitations and improve user experience.

7.4 Material exploration

We envision a range of applications for TacTex in the realm of apparel. Imagine gloves, wristbands, or vests crafted with the TacTex interface in constant contact with the skin. For optimal skin-electrode contact in such applications, the textile would ideally possess elasticity, a feature not present in the current material. To cater to these potential applications, we are considering the integration of elastic yarns in future iterations.

7.5 Experiment Design

The sample size for the studies was relatively small, and the participants were all healthy young adults, which may limit the generalizability of our findings to other populations. Future studies could recruit a more diverse sample to evaluate the effectiveness of the TacTex interface across different age ranges, health statuses, and cultural backgrounds.

Although we envisioned possible applications with TacTex stimulating other body areas, such as forearms, cheeks, and the neck, the present work has not studied electrotactile stimulation on body areas other than the fingertips. We will address these limitations in future work.

While the textile is capable of 1mm electrode spacing, our experiments utilized the 2mm configuration. This choice was driven by the fact that a 2mm spacing suffices for a broad spectrum of interaction requirements. Nonetheless, we recognize the remarkable human tactile sensitivity and the increasing demand for tactile sensors and displays approaching the human perception limits [45, 51]. Consequently, our future research aims to engage participants in exploring the potential of TacTex at 1mm intervals or even finer spacings.

7.6 Driving circuit

Our driving circuit is meticulously designed to minimize latency and electromagnetic interference. At its core, the circuit utilizes an STM32F207 microcontroller and is predominantly built from MOS components. To address latency, we integrated the STM32F207IET6 microcontroller, boasting 176 pins. Each pair of its built-in GPIOs governs a tri-state switch, enabling 128 GPIOs to oversee 64 tri-state switches collectively. For inter-microcontroller communication, we adopted the RS485 serial port, which not only facilitates rapid data transfer but also curbs electromagnetic interference. These design decisions ensure our circuit aligns with our specifications. However, intrinsic properties of MOSFETs, such as parasitic capacitance, do contribute to a slight delay in switch operations. Our oscilloscope readings pinpoint this lag at an average of $3\mu s$ from the release of the control signal to the switch's designated action. Moreover, the high-voltage, high-frequency stimulation and scanning pulses produced can induce crosstalk in adjacent circuits. Phasing out bulky high-voltage sources remains a hurdle, as does the incorporation of large-packaged microcontrollers and numerous discrete components, which impede the drive circuit's miniaturization. These constraints limit the wider adoption of TacTex devices, especially in compact wearables and athletic equipment. As we progress, our goal is to elevate the TacTex device experience through judicious component choices, sophisticated circuit design, and fine-tuned driver programming.

7.7 Limitations of Example Applications

Although we present several application prototypes that exploit the interface's sensing and stimulating capabilities, these applications are not fully functional, and many envisioned applications remain unexplored. This limitation hampers our ability to thoroughly investigate and evaluate the application of electrotactile sensations and sensing methods in practical scenarios. Moving forward, we intend to further develop representative applications, thereby facilitating a more in-depth exploration and assessment of TacTex for real use cases.

8 CONCLUSION

In conclusion, the TacTex interface has been developed to provide high-resolution electrotactile stimulation and touch tracking. It employs innovations in textile design, driving systems, electrotactile stimulation, and touch tracking. The use of multi-layer woven structures with conductive weft and warp electrodes enables the creation of densely and precisely embedded electrodes, which can be modified to alter electrode sizes and distances, electrode patterns, and visual appearance. The driving system provides a constant current, operates switches that control the electrical stimulus waveforms and locations, and monitors voltage changes while scanning electrodes to track touch on the textile. The TacTex interface can stimulate a wide range of haptic effects, including different sensation qualities, static patterns, and dynamic patterns. Touch tracking is achieved using the same electrodes and pulse amplitude as the stimulating haptic effects, and methods have been developed to ensure that touch-tracking stimuli do not cause any noticeable disturbance to the designed haptic effects. Overall, the TacTex interface has great potential for applications in weaving haptics into everyday textiles.

ACKNOWLEDGMENTS

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