Tacttoo: A Thin and Feel-Through Tattoo for On-Skin Tactile Output

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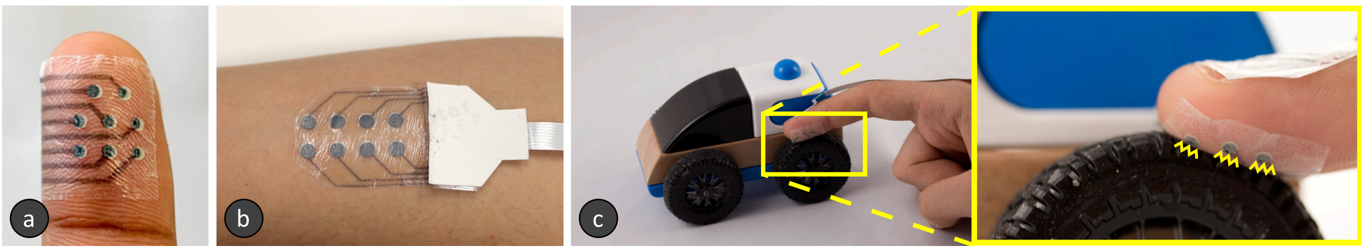

Figure 1. A Tacttoo rub-on tattoo enables feel-through and high-density tactile output. With less than $35\mu m$ in thickness, it closely conforms to fine structures of the skin. Tacttoos can be custom-designed for various body locations and taxel densities, and fabricated using DIY tooling.

ABSTRACT
This paper introduces Tacttoo, a feel-through interface for electro-tactile output on the user's skin. Integrated in a temporary tattoo with a thin and conformal form factor, it can be applied on complex body geometries, including the fingertip, and is scalable to various body locations. At less than $35\mu m$ in thickness, it is the thinnest tactile interface for wearable computing to date. Our results show that Tacttoo retains the natural tactile acuity similar to bare skin while delivering high-density tactile output. We present the fabrication of customized Tacttoo tattoos using DIY tools and contribute a mechanism for consistent electro-tactile operation on the skin. Moreover, we explore new interactive scenarios that are enabled by Tacttoo. Applications in tactile augmented reality and on-skin interaction benefit from a seamless augmentation of real-world tactile cues with computer-generated stimuli. Applications in virtual reality and private notifications benefit from high-density output in an ergonomic form factor. Results from two psychophysical studies and a technical evaluation demonstrate Tacttoo's functionality, feel-through properties and durability.

CCS Concepts
•Human-centered computing → Haptic devices;

Author Keywords
On-Body Interaction; Skin; Tactile Display; Electro-Tactile; Tattoo; Fabrication; Printed Electronics; Wearable Computing.

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INTRODUCTION
Existing wearable tactile displays commonly use thick, rigid or rather inflexible mechanical components. This prevents deploying tactile output on many important body locations that are curved, undergo deformation, and demand the natural tactile sensation to be unaffected. For instance, the fingertip has the highest acuity of tactile perception on the human body and therefore is a highly desirable location for tactile output. However, for ergonomics and day-to-day wearability, a finger-worn device should not inhibit the user from perceiving natural tactile stimuli (such as textures, ridges, corners, edges, etc.) when fingers interact with real-world objects. Therefore, a growing demand exists for *feel-through* tactile interfaces. Such interfaces allow the user to naturally feel physical objects or surfaces across the interface, as if no interface was present at all, while at the same time delivering computer-generated tactile output. This property makes it possible to augment virtually any object with tactile output while preserving its natural tactile cues for interaction.

Feel-through tactile interfaces enable new applications in the emerging areas of tactile augmented reality [5, 10] and skin-based interfaces [64, 46, 35]. For instance, product designers can explore real tactile features of a physical prototype, while custom interactive feedback is rendered simultaneously on the fingertip. A feel-through display on the fingertip is also compatible with various kinds of dexterous interactions, such as writing with a pen or leafing through pages of a document. Moreover, it enables novel types of on-skin interfaces that provide dynamic tactile output while still allowing the user to feel static tactile body landmarks, such as knuckles, wrinkles, or veins, which provide guidance and orientation during eyes-free interaction [57].

However, realizing a feel-through tactile interface has to overcome several demanding technical challenges: 1) The interface has to be extremely slim and deformable to pass external tactile stimuli without notable degradation. 2) The tactile sense is distributed across the body over complex geometries and deformable surfaces. 3) The human tactile sense has a high spatial acuity and temporal resolution. Accommodating these in a wearable form factor is inherently difficult. In light of these challenges, it is not surprising that recent work on epidermal electronics and interactive skin [65, 46, 64, 40, 35] has investigated sensing and visual displays, but not tactile output.

This paper contributes Tacttoo, a new class of feel-through tactile interface that is integrated inside a temporary tattoo. Tacttoo is designed and fabricated to be safely and ergonomically worn on the skin and directly deployed on challenging body geometries, such as the finger or the forearm. It contains a *dense array of electro-tactile taxels* at a density comparable with the electro-tactile acuity of skin. With less than 35 μm thickness, Tacttoo is *the thinnest tactile interface* presented in the literature (by a factor of 3 compared to work in materials [51, 14] and a factor of 8 compared to recent work in HCI [36]). Tacttoo's thin and flexible form factor allows the interface to be conformal with the skin and for the first time enables *feel-through tactile output*.

We present how to *design and fabricate Tacttoo tattoos of custom dimensions* using DIY equipment with commercially available materials. We chose electro-tactile stimulation as the underlying working principle as it is compatible with slim interfaces [51, 14], power efficient and can generate tactile stimulation comparable with mechanical actuators [70]. Unlike prior on-skin interfaces designed for sensing, electro-tactile interfaces require skin-exposed electrodes that inject significant currents ($\sim 1-2mA$) into skin; therefore, a consistent and firm electrical contact is necessary. To establish this electrical contact between electrodes and the skin, we introduce a *novel layered approach* that integrates screen printing and laser patterning to realize micro-spring mechanisms. Moreover, to account for the added safety requirements for a device that is worn on the skin, we present a *three-layer architecture for safe electrical operation* of skin-worn electro-tactile devices.

Two psychophysical experiments and a technical experiment with users validate the *functionality, feel-through properties* and *durability* of Tacttoo. The results demonstrate that Tacttoo retains most of bare skin's natural tactile sensation, while it is capable of rendering electro-tactile stimuli at a high fidelity. To demonstrate new usage scenarios enabled by Tacttoo, we present five applications in the areas of tactile augmented reality, dynamic on-body tactile landmarks, virtual reality, and private notifications.

This technical contribution opens up a new space for tactile augmented reality where high-density tactile output is overlaid and aligned with natural tactile stimuli of the real world at various body locations without any instrumentation of the environment.

RELATED WORK

Tactile or cutaneous sensations are perceived through mechanoreceptors in the skin [42, 25] and can be an effective medium to communicate information to humans [7, 26]. Wearable tactile displays allow for always-available, subtle and private output [6, 63, 49, 62, 58, 26, 39]. The most commonly used technology for wearable tactile interfaces, including commercial products, is vibro-tactile output. Other forms of actuations methods such as thermal [49, 52, 66], pneumatic [20, 2], shear forces [23], ultrasound [68, 55], wind flow [43] and brushing [58] have been demonstrated.

The vast majority of tactile interfaces use rigid mechanical actuators with rather large form factors, which has impacts on the wearability of the system. Furthermore, when deployed on the body, rigid interfaces inhibit the natural tactile sensation of the skin. In contrast, *MagTics* showed a flexible wearable tactile interface that enabled unique interactions and application possibilities [48]. Recent advancements in material sciences have enabled thin and flexible tactile actuators [24, 16], for instance a $\sim 5mm$ thick magnetic and thermal actuator [17], $1mm$ using organic transistors [37], and $255\mu m$ using flexible electro-active polymer (EAP) [22].

Electro-tactile interfaces provide a means to implement tactile displays without rigid mechanical actuators. This provides a significant advantage for wearable applications where small, lightweight and flexible interfaces are desirable. Electro-tactile interfaces use two or more electrodes in contact with the skin and a controlled electric current pulse to directly stimulate nerve stems of mechanoreceptors, which the brain interprets as mechanical vibrations [60, 32, 70, 4, 39]. They can deliver versatile tactile properties such as a wide band of frequencies at a high tactile acuity [54, 4]. This principle has been investigated and its functioning has been extensively confirmed through psychophysical studies [9, 33, 21, 54]. Electro-tactile interfaces have been demonstrated for various areas of the body, such as the fingertips [34, 4, 39, 30, 21, 59, 36], forearm [21, 51, 14], abdomen [29, 60], back [9] and tongue [4, 61].

Tang used micro-fabrication to develop a $200\mu m$ thick, 16 taxel electro-tactile interface for the roof of the mouth [61]. Popovic-Maneski et al. [51] and Franceschi et al. [14] showed the implementation and functionality of a 12 taxel electro-tactile interface on the forearm, printed on a $125\mu m$ thick flexible polymer substrate. Kato et al. significantly reduced the fabrication complexity of electro-tactile displays by using a commodity inkjet printer. The resulting interface is on a $270\mu m$ substrate and contains two taxels on the fingertip [36]. Despite the very impressive form factors, these devices have not yet reached the thickness required to create conformal contact with skin [27].

Our tactile feel-through concept is inspired by pioneering work on Tactile Augmented Reality (TAR) by Bau et al. [5]. We also drew inspiration from flexible on-skin interfaces [40, 64, 46, 65] which contain sensors and displays (but not tactile output) that are thin enough to allow the user to feel-through natural tactile body landmarks [65, 57]. Indirect tactile actuation technologies [5, 71, 69] do not need to overlay the interaction area and hence provide an alternative to feel-through interfaces. In contrast, our proposed feel-through tactile interfaces enable high-density output to capitalize on the tactile acuity of human skin, can be deployed on a wide range of body locations, and at a $35\mu m$ thickness, allow users to feel external tactile stimuli through the device.

DESIGN GOALS FOR TACTTOO INTERFACES

We propose Tacttoo as a new class of *feel-through* tactile interfaces for use on the human skin. In this section, we outline important requirements and opportunities for the design and implementation of such tactile devices from the perspective of human computer interaction. These considerations guided the interfaces presented in the remainder of this paper and can also serve as guidelines for future implementations.

Feel-Through

Tactile sensation is vital for our everyday activities. Many locations on the body, and most centrally the fingertips, require the perception of external tactile stimuli [50, 67]. We define a *feel-through* interface as an interface which, while worn on the skin, does not degrade or only marginally degrades the cutaneous sense of external natural stimuli. Hence, the interface allows the user to feel through it and perceive real-world tactile stimuli through the device. Note that this definition includes, but extends beyond the common requirement of skin-worn devices to be slim, lightweight, and ergonomic.

A feel-through interface can be realized using two means:

1) Passive feel-through: Passive feel-through interfaces are designed and fabricated such that natural tactile stimuli can mechanically penetrate the device without any active intervention. In the visual modality, this is analogous to an optical see-through display. Tacttoo belongs to this class.

2) Active feel-through: Active feel-through interfaces are designed to actively capture natural tactile stimuli using sensors and replicate the tactile stimuli on the skin using actuators. While implementations of such devices exist, the fidelity of tactile replication is still rather low [34]. In the visual modality, this is analogous to a video see-through display.

Curved and Deformable Body Geometries

Skin is the largest organ of the human body and sensitivity to tactile stimuli is an integral feature. Therefore, unlike visual and auditory sensation, tactile sensation is not spatially concentrated. While deploying actuators on the skin provides a great opportunity for creating tactile interfaces, the majority of skin surface has complex geometry, undergoes deformation during body movement, and is subject to considerable mechanical strain. For instance, the surface of the fingertip is doubly curved and considerably deforms during contact. Conventional mechanical actuators are inherently intrusive and hard to wear on such complex geometries because of their rigid and bulky form factor. In contrast, Tacttoo interfaces should support the geometries on the body. This requires a flexible and conformal interface, similar to previously demonstrated skin-worn sensors and displays [64, 46, 65].

High Spatial Density and High Temporal Resolution

The cutaneous sense has a comprehensive set of distinctively identifiable stimuli qualities that are based on spatial and temporal features of the sensation [15, 42]. The sensitivity to these different qualities varies across different body locations [42]. For instance, the human fingertip has a high spatial acuity with a two-point discrimination threshold between 1 and 2 mm, whereas the threshold at the forearm is between 8 and 10mm [42]. Temporally, different mechanoreceptors on the body can sense different frequencies of stimuli, ranging from less than 5Hz to around 400Hz. In a tactile interface, controllability of these stimulus properties is important to deliver a high-quality tactile experience. For example, the spatial acuity could be leveraged to render shapes, directions, and locations [7, 4]. In addition, frequency of stimuli could be used to manipulate the perception of tactile features [71].

Active and Passive Tactile Perception

Based on the physical means used to acquire stimuli, tactile perception can be divided into two types. In *active tactile perception*, the user perceives the sensation by moving the skin on an object or surface, for instance to perceive the texture. In contrast, in *passive tactile perception*, the user perceives the sensation without any active movement, for instance when in contact with a vibrating object. Depending on the technology used, only one of the two types may be supported, e.g., active tactile only in [5]. However, as active and passive tactile senses are important modalities and complement each other, Tacttoo should support both active and passive tactile exploration.

No Modification of the Environment Required

A Tacttoo device should be able to provide tactile output independently of what object or surface the user is touching. It should be independent of the object's type (i.e., if the object is instrumented or not), material (mechanical properties such as rigid or soft, electrical properties such as conductive or not), geometry, or object status (i.e, mobile, fixed; live, inert; etc.). Of note is that it should not be required to modify the environment or objects in any way. This is critically important in the context of augmented reality, where augmenting the myriad of objects in a real environment is the goal. Furthermore, in virtual reality applications there may be no real object present. Therefore, the device should also be capable to deliver tactile output without any contact with the environment (in mid-air).

Safety, Comfort and Robustness

Safety, comfort and robustness are vital design aspects of a wearable system and even more important in the context of an on-skin interface. First, skin compatibility materials should be selected to prevent skin irritation and allergic reactions. Secondly, electrical safety must be assured to prevent electrical shocks. Furthermore, for ease of operation, the device should be conformal and compatible with the mechanical properties of skin. Lastly, the device should be mechanically robust to withstand interactions with the real environment as well as movements and deformations that occur when the body moves.

IMPLEMENTATION OF TACTTOO

We present the first approach to fabricating electro-tactile interfaces in a skin-conformal form factor. We implement Tacttoo as a temporary rub-on tattoo. With a thickness of less than $35\mu m$, it is—to the best of our knowledge—the thinnest wearable tactile interface presented in the literature. This unique form factor enables us to create a feel-through tactile interface that provides computer-generated tactile output while still allowing natural tactile stimuli to pass-through to the mechanoreceptors on the skin.

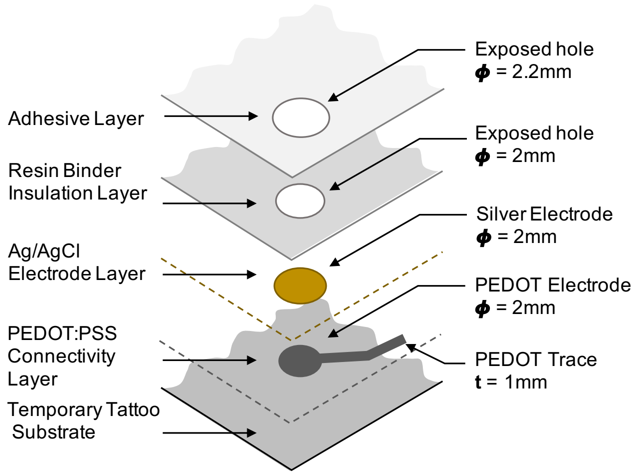

Figure 2. Layered fabrication of Tacttoo

The main technical challenge we had to address is to fabricate conformal interfaces that ensure a consistent electrical contact between the exposed electrodes and skin, despite the significant currents required for electro-tactile stimulation and without requiring the use of wet gel to improve conductive skin contact. We present a new layered approach that is fabricated using screen printing and laser patterning. It realizes micro-springs for improved skin contact of electrodes, while also containing the necessary interconnects and isolation required for electro-tactile stimulation. In addition, to account for the added safety requirements of a skin-worn device, we present an architecture for mobile control electronics that ensures safe operation of skin-attached electro-tactile stimulation.

Digital Design of Customized Tacttoo Interfaces

The rub-on tattoo is fabricated from a digital vector design. Hence, it can be easily customized for different body locations and applications. The basic building block for designing a Tacttoo is a circular electrode that is exposed to the user's skin. It represents a tactile pixel or a *taxel*. An interface contains at least two electrodes. Multiple taxels can be individually placed at custom locations on the interface. Alternatively, they can be arranged in a matrix of customizable dimensions (number, size and density of taxels).

The size of a taxel and spacing between them is decided based on the application requirement and the body location where they are deployed. Our prototypes demonstrate a minimum taxel size of $2mm$ diameter with $4mm$ center-to-center spacing. This results in a density comparable with the electro-tactile acuity of the index fingertip, which is the location with highest tactile acuity on the body [42, 54, 34].

The design of our Tacttoo *prototype for use on the fingertip* consists of an array of 8 equispaced circular electrodes arranged into 3 rows (containing 2, 3, and 3 electrodes, respectively) (Figure 1-a). The electrode diameter is $2mm$ with $4mm$ center-to-center spacing. The total actuating area is $10mm \times 10mm$, adequate to cover an adult's fingertip [12]. Each individual electrode in the array is separately connected to an actuating circuit using conductive traces which are isolated from the skin. Hence, individual taxels can be controlled independently. This enables Tacttoo to go beyond single-point stimulations and realize complex tactile renderings, exploiting the spatial acuity and temporal resolution of tactile perception.

Another prototype design is tailored for *use on the forearm* (Figure 1-b). It has a 4×2 array of taxels with an increased electrode spacing of $9mm$ to match the lower tactile acuity of the forearm [42, 54]. The diameter of each electrode is set to $5mm$, similar to previous interfaces [14]. This design results in a larger output area ($23mm \times 41mm$) to support the larger surface area available on the forearm.

Fabrication of Tacttoo Temporary Tattoo

Tacttoo is designed not to impede the natural tactile sensation of the wearer. This requires a significant reduction of the thickness of the interface to make conformal contact with skin. As shown in prior work [27], the majority of a membrane as thin as $100\mu m$ still does not contact skin and instead encloses large air gaps. In contrast, the vast majority of a surface of a $36\mu m$ thick interface creates conformal contact with skin.

Moving below this critical thickness is even more pivotal in the case of electro-tactile interfaces. These require skin-exposed electrodes that inject significant currents ($\sim 1-2mA$) into the skin. At these current levels, inconsistent contacts lead to sparks that rapidly damage the electrodes (similar to [36] Fig.4) impeding tactile stimulation, and also lead to undesirable sensations, such as heat. Therefore, exposed electrodes must ensure consistent and firm electrical contact with skin. In addition, the small electrode dimensions and the desired ease of use prevent using conductive gel, which has been used in prior work to enhance contact with the skin [51, 14].

We resolve this challenge by carefully selecting a combination of elastic and rigid materials with different thicknesses to create a micro-spring mechanism that pushes electrodes onto the skin. The resulting tattoo does not require any external mechanical fixtures or conductive gel to ensure consistent skin contact of electrodes.

A Tacttoo tattoo consists of three functional layers that are screen printed on a substrate layer of commercially available temporary tattoo paper[1]. We use hobbyist-level screen printing equipment, as used previously in HCI [47, 46, 65]. We use commercially available silver nanoparticle-based Ag/AgCl conductive ink[2], polymeric PEDOT:PSS conductive ink[3], and heat curable resin binder[4] as the insulation material.

Fig. 2 shows the layers: A connectivity layer is printed using PEDOT:PSS ink; it contains the inner routings for connecting the controller to the electrodes. The skin-exposed electrode layer is printed using Ag/AgCl ink. Ag/AgCl is generally considered skin-safe and most commonly used in electrodes that capture biological signals on skin, including in [51, 14]. This layer is covered by an insulation layer, printed using resin

[1] Silhouette Temporary Tattoo Paper
[2] Gwent - C2131014D3, $0.1\Omega/\square$ - layer thickness (LT) of $20\mu m$
[3] Gwent - C2100629D1, $500-700k\Omega/\square$ - LT of $0.5-1.5\mu m$
[4] Gwent - R2070613P2

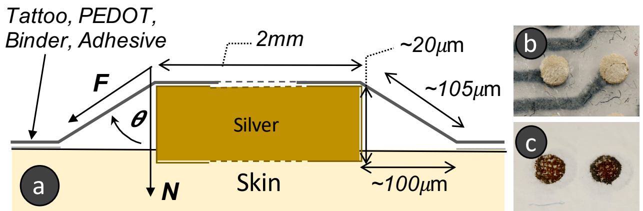

Figure 3. a) Micro-spring mechanism created by the tattoo substrate and the slightly thicker silver electrode; b) Micro-spring electrodes remain intact, while c) otherwise electrodes would deteriorate due to sparks.

binder, which insulates the connectivity traces while keeping the electrodes exposed. After printing, each layer is heat cured[5]. The topmost layer is the adhesive that bonds the temporary tattoo to the user's skin. It is prepared by laser-cutting a sheet of temporary tattoo adhesive to remove the adhesive at areas that overlap with electrodes. The adhesive layer is then bonded on in alignment with the printed electrodes.

By using two different conductive inks that result in layers of different thickness, micro-springs are formed (see Figure 3-a). We print the interconnect using PEDOT:PSS, resulting in very slim and flexible traces ($\approx 2\mu m$). In contrast, we use silver-based ink for the electrode layer ($\approx 20\mu m$). The considerably thicker electrode strains the tattoo substrate, which in turn creates a normal force that pushes the electrode towards the skin. As shown in Figure 3-a, we keep a gap without adhesive around the electrode of $100\mu m$ width. The added height of the electrode results in stretching the tattoo paper from 100 to 105 microns. This creates a tensile force of approx $F = 20mN$ (Young's modulus of tattoo paper approx. $1GPa$), in turn resulting in a normal force of approx. $N = 13mN$.

This material combination is a result of an iterative experimentation process, in which we also tested using PEDOT:PSS for both the electrode and the traces (failed due to insufficient skin contact) and using silver for both (inconsistent contact resulted in rapid deterioration of electrode as shown in Fig 3-c). In contrast, our proposed combination results in durable skin contact. This is demonstrated by the results of our durability tests presented below and evidenced by Figure 3-b, which shows an electrode after 1 hour of use on the skin, with no visible deterioration.

Fabrication of the complete set of layers typically takes about one hour. Printing time can be significantly reduced by combining multiple Tacttoos into one printing batch. Once the Tacttoo is ready, it can be transferred to the skin using the water transfer method used in previous work [46, 65].

Three-Layer Architecture for Electrical Safety

Electro-tactile interfaces need proper control of stimulus current to assure electrical safety for humans. The commonly used technique to control and avoid unsafe current levels is a closed-loop implementation, in which a microcontroller controls the current source with a measured feedback [31, 34]. However, this solution depends on the correct functioning of the microcontroller, which cannot be guaranteed in the light of software or firmware bugs and malicious attacks [41]. This is particularly problematic with a permanently skin-worn solution: in contrast to touching an electrode on an external object, where a "let go" response [13] would be a natural safety response to an electrical shock, the user cannot easily let go of a skin-worn electrode.

To ensure safe operation of skin-worn electro-tactile systems, we contribute a three-layer architecture for the electrical safety of stimulus current. It provides a comprehensive safety infrastructure for electro-tactile simulation, comprising continuous current control, accidental over-current protection for the user and leakage current protection to the surroundings. The architecture adds two new layers to the existing approach of microcontroller-based safety. These new layers are fully implemented in hardware and hence not vulnerable to bugs in software or firmware or to software attacks. Of note is that they do not have any effects on the tactile sensation rendered by the system. The three-layer architecture is generic and applicable to any electro-tactile interface.

Layer 1: Current Control Loop: Similar to electro-tactile controllers presented in the literature [31, 34, 36, 70, 51], our first safety layer implements a current control loop that is controlled by a microcontroller. The microcontroller (Teensy 3.5, 12 bit digital-to-analog converter DAC) controls a voltage-to-current converter (V-to-I) implemented using a current mirror built with NPN transistors (ZTX958), N-channel DMOSFET (VN2460) and an Op-Amp (MCP6021) (Figure 4-a-1). The V-to-I is designed to generate controlled currents from 0 to $3.3mA$, with $16.5\mu A$ steps (200 steps) according to the input from the microcontroller. This prevents current reaching unsafe levels independent of changes in skin resistance or any short circuits. The controlled current is then applied to the desired electrode in the interface using a multiplexer (Supertex HV513). To realize a closed control loop, the actual current passed through the system is measured using a fixed sensing resistor ($R_{si} = 1k\Omega$) and fed back to the micro-controller through its 12-bit analog-to-digital converter (ADC).

Layer 2: Over-Current Protection: In case of a malfunction in the microcontroller, safety at layer 1 could fail, leading to increased current levels at electrodes. The second safety layer prevents injecting over-currents independent of the microcontroller's functioning. In this layer, the current measured at R_{si} is compared against a fixed voltage source $V_s = 3V$ using a high common-mode voltage differential amplifier (TI-INA149). Any current exceeding $3mA$ (i.e., $3V$ across R_{si} is $3V/1000\Omega = 3mA$) deactivates all electrodes using the enable/disable port in the multiplexing circuit (Figure 4-a-2).

Layer 3: Leakage Current Protection: Tacttoo is designed to be worn on body locations that undergo external mechanical strain. In a worst-case scenario, this may damage the insulating layers and expose conductive parts to the outside of the device, resulting in leakage currents. We design a third safety layer that detects leakage currents (Figure 4-a-3). An additional measurement resistor R_{sc} ($= 1k\Omega$) measures the current that is collected from the multiplexer. A voltage comparator (made with INA149) with hysteresis of 0.1V (equivalent to

[5]PEDOT, Ag/AgCl and resin binder cured at 80 °C for 3, 3 and 5 minutes respectively.

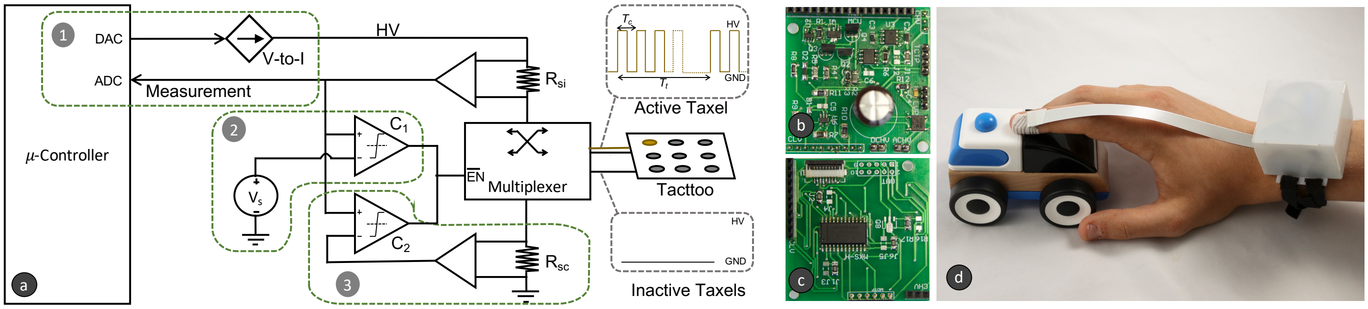

Figure 4. Tacttoo control system; a) Three layer electrical safety architecture; b) Implementation of control and safety electronics; c) Modular multiplexing circuit which can be daisy-chained to increase the number of taxels; d) Complete mobile setup of Tacttoo with transfered tattoo, FPC connection and the control unit.

0.1mA across R_{sc} or R_{si}) compares it with the injected current measured at R_{si}. In the case of a difference in currents, it triggers the enable/disable port in the switching circuit to disable all electrodes. Hysteresis is used to avoid unstable fluctuations due to transient effects of the electrical system [38]. Like layer 2, this layer is fully implemented in hardware.

Tacttoo Controller Implementation

The Tacttoo hardware controller is implemented as a fully wearable system. It consists of the microcontroller, the circuit, a Bluetooth module (Guangzhou HC-05), inverter (Adafruit 317) and a rechargeable battery (350mAh Li-Po). The setup is depicted in Figure 4. Tactoo V-to-I operates at 250V DC and can deliver 1mA of current to large skin resistances up to $= 250k\Omega$. The multiplexer excites the active electrode with a positive (anodic) current, while all other electrodes are grounded. The stimulus signal consists of current pulses with a pulse width of $T_c = 200\mu s$, leading to a carrier frequency of $f_c = 2.5kHz$. f_c is used to modulate the tactile frequency f_t (0 to $200Hz$ - T_t as shown in Figure 4-a). This is the actual frequency of sensation the user perceives [32]. Both f_c and f_t are controlled using the microcontroller by rapidly switching circuits in the multiplexer. We designed the Tacttoo controller following a modular circuit design where one circuit consists of one multiplexing IC, resulting in 8 channels. This circuit can be cascaded to further extend the taxel count of Tacttoo in multiples of 8. The wearable unit can operate for 5 hours on one charge. The wearable controller is $3.5cm \times 5.5cm \times 5cm$ in dimensions and weighs $100g$. The rub-on tattoo is connected to the controller using an FPC connector.

Sensing of touch input can be optionally integrated into the tattoo by adding a layer of tattoo paper with PEDOT-printed electrodes for loading-mode capacitive touch sensing, similar to the touch sensing demonstrated in [46, 65]. The Teensy microcontroller reads self capacitance values at every $10ms$.

We have implemented a control application using *Electron.js* (JavaScript, CSS, HTML) that runs on a MacBook Pro (Intel Core i5, 16GB RAM) and connects to the Tacttoo wearable controller using a wireless Bluetooth connection. Stimulation data is communicated using a stream byte array consisting of taxel (0-8), stimulus intensity (0-200) and ON time (0-200ms) at $1kHz$ frame rate. The microcontroller reports back the measured voltage and current across the skin and optional capacitive readings for touch input.

APPLICATIONS

The unique *feel-through* characteristic of a Tacttoo tactile interface opens up new opportunities for interaction in various application areas. We demonstrate these in five application examples in tactile augmented reality, on-body interfaces, tactile output in virtual reality, and private notifications.

Tactile Augmented Reality on Physical 3d Models

In augmented reality (AR), see-through and hear-through interfaces have been key enablers to realize visual and auditory augmentation of the environment [8, 45]. In contrast, tactile augmentation remains underexplored, with only few approaches presented so far [5, 71]. The tactile feel-through property of Tacttoo enables us to seamlessly align real-world and virtual tactile stimuli on a physical object, creating *Tactile Augmented Reality* (TAR) applications [3].

We developed a TAR application that supports designers in exploring dynamic and localized tactile properties of 3D models (see Figure 5-a). It accounts for the high relevance of physical prototypes in design processes, while adding dynamic computer-generated content.

The application lets designers experience how engine vibrations propagate across a car. The physical model of the car, shown in Figure 5-a, contains rich tactile cues, including curvatures, ridges, varied surface geometries and material properties. The designer can feel these tactile cues through the tattoo while engine vibrations and their propagation across the car are virtually overlaid using the electro-tactile interface. For instance, as shown in Figure 5-a, a designer wearing Tacttoo on the index fingertip touches the tire and can directly feel the rubbery material alongside the detailed surface geometry. At the same time, taxels stimulate at the respective frequencies at which the tire vibrates. Touching another part of the car model will make the user feel different natural cues, which are augmented by computer-generated tactile output rendering the vibrations at this location. This principle can be generalized to other applications in design, engineering and architecture where simulating dynamic tactile information is important.

For easing the prototypical implementation, we track the location of the finger respective to the 3D model using an OptiTrack system. In future implementations this could be easily replaced by a wearable solution, e.g., based on a body-mounted camera.

Augmenting Paper Prototypes with Tactile Feedback

Feel-through tactile interfaces are also vital in any task that involves dexterous manipulation of objects. For instance, paper-based activities centrally rely on dexterous grasping, flipping or leafing through sheets of paper. When worn on the finger, classical actuators would impede tactile perception and physical manipulation skills which are key for manipulating paper. In contrast, Tacttoo is compatible with these tasks.

We have implemented an application that supports UI paper prototyping. With a growing availability of tactile feedback in commercial mobile and wearable devices, a low-fidelity means to design and test tactile feedback is becoming important. Our application therefore augments sketched user interface prototypes with dynamic tactile feedback (see Figure 5-b). A sketch is first captured using a digital camera. To test the design, the user wears a Tacttoo on the index finger. When the user touches a sketched widget, dynamic tactile output is provided. For instance, active buttons provide a "click" feedback as a short burst of taxel vibrations, a slider widget renders the current location of the slider knob and continuous vibration feedback while the user moves the slider.

Dynamic Tactile Landmarks for Eyes-free On-body Input

On-skin interaction is an emerging area of growing importance [19, 72, 64, 56]. Tactile features of the human body, such as knuckles and wrinkles, have been shown to offer affordances and landmarks that can guide the user during eyes-free on-body input [65, 57]. However, these landmarks are static.

Tacttoo enables tactile augmentation of the human body to create *dynamic* on-body landmarks at desired locations. At the same time, it allows natural body landmarks to be felt through the interface. In contrast, classical tactile interfaces would fail since they firstly occlude natural body landmarks and secondly create permanent tactile cues themselves.

Our application demonstrates dynamic tactile landmarks for eyes-free interactions on the forearm (see Figure 5-c). The interface provides on-skin buttons to play and pause a music player. Buttons are centered around a natural landmark on the forearm (a vein as proposed in [65]), which helps users identify the vicinity of the buttons. When the Tacttoo-augmented index finger touches a virtual button, a tactile stimulation is generated. Each button has its own cue (vibration frequency). This enables the user to correctly localize and identify the functionality of the interface during eyes-free interaction.

To illustrate an alternative where input sensing and tactile output are integrated in a single Tacttoo, we have implemented the same application using a Tacttoo that is worn on the forearm (see Figure 5-d). It contains a capacitive touch sensor and two active areas that provide tactile stimulation when the location of the virtual landmark is touched.

Tactile Rendering in Virtual Reality Applications

Tacttoo provides a self-contained high-density array of taxels in an ergonomic and fully mobile form factor. This can facilitate virtual reality applications.

We have implemented an application that demonstrates the use of Tacttoo for rendering tactile properties of virtual 3D objects

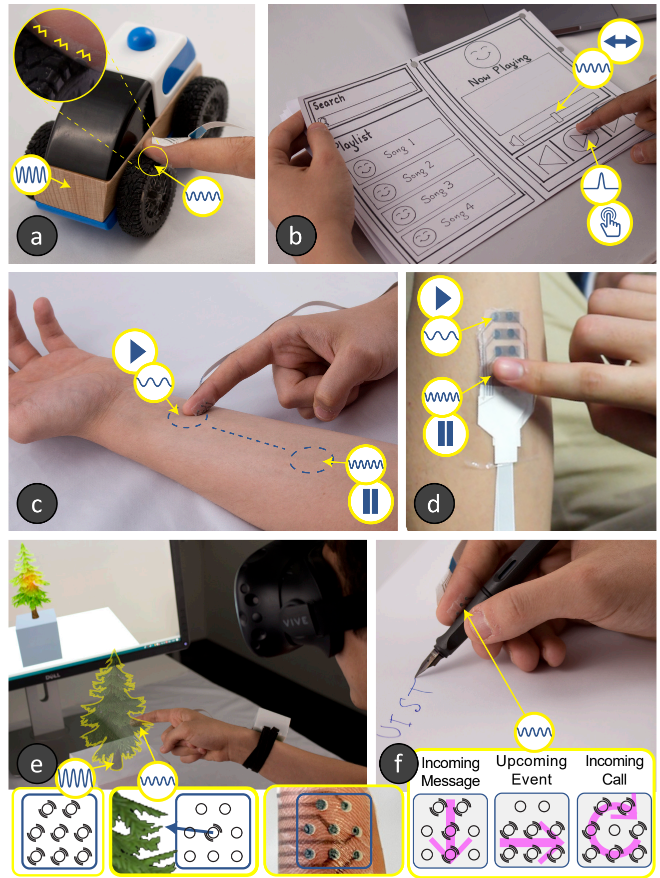

Figure 5. Interactive example applications. a, b) Tactile augmented reality; c, d) Dynamic tactile landmarks for on-skin interactions; e) Tactile output in virtual reality; f) Private tactile notifications

(see Figure 5-e). 3D objects are rendered using Unity3D and displayed on a virtual reality headset. The user wears a Tacttoo interface on the index fingertip. The user's finger position is tracked and visualized in the 3D scene. When the user is touching a virtual object, collisions between the finger model and multiple leaf geometries of the tree are used to stimulate different locations on the fingertip with Tacttoo taxels in real-time. For instance, sharp ends of virtual branches are rendered as single taxel actuations at low frequencies, while flat surfaces actuate multiple taxels at high frequencies.

Private Notifications

Tacttoo is particularly well-suited as an interface for delivering private notifications, as it firstly can be ergonomically worn on challenging body geometries (e.g. fingertips) and is compatible with dexterous everyday activities. Secondly, it can be worn invisibly on hidden areas on the body, e.g., under clothing or on the inner side of the forearm. Lastly, in contrast to mechanical actuators, the electro-tactile interface of Tacttoo does not produce any audible noise. Therefore it enables fully private tactile notifications in social situations, for instance during a business meeting.

We have implemented a Tacttoo interface that delivers private notifications on the fingertip. It can inform the user about an incoming message, an incoming call, and an upcoming meeting. Following the design principles of tactile icons [7], the interface communicates these different types of notification using variations in direction and temporal patterns. The dense taxel matrix of Tacttoo can render spatio-temporal patterns including linear and circular movements in multiple directions (see Figure 5-f). For an incoming message, taxels are sequentially ($200ms$ SOA at $30Hz$) actuated from the tip of the finger towards the palm for two iterations. To signal an incoming call, 7 outer taxels of Tacttoo are sequentially activated, creating a clockwise circular motion. Finally, calendar notifications create three swings of tactile stimulation from left to right. This demonstrates the expressiveness of the device beyond simple one-point, one-type output.

EVALUATION

To validate the functionality of Tacttoo as a wearable feel-through tactile interface, we investigated three main questions: 1) Can Tacttoo deliver tactile sensation on skin? 2) Can users feel external tactile stimuli through Tacttoo? 3) Can Tacttoo be worn on demanding body locations robustly and durably? To answer these questions, we conducted two psychophysical studies and a technical evaluation with users. Note that we have not evaluated spatial and temporal discrimination thresholds of electro-tactile interfaces, since these have been identified in prior work [34, 53] and directly apply to Tacttoo.

Functionality of Electro-Tactile Stimulation with Tacttoo

Tacttoo is considerably thinner than prior electro-tactile displays and uses a DIY fabricated, novel micro-spring loading mechanism. In order to verify that Tacttoo can generate sufficient stimuli to elicit a tactile sensation on the skin, we conducted a psychophysical study, which identified the absolute threshold of sensation delivered by Tacttoo.

Participants

Ten participants (3 female, 1 left handed, aged from 24 to 30) were recruited. None of them reported any health condition that could have affected their performance in this experiment.

Method

A Tacttoo with an array of 2×2 taxels ($2mm$ diameter with $4mm$ center-to-center spacing) was selected for the experiment, since it represents the basic building block of a Tacttoo taxel matrix with the smallest electrode size and the highest taxel density. The tattoo was applied on the center of the index fingertip of the participant's dominant hand.

We used the classical *method of limits* [18, 28] with a random, double staircase-method (each staircase with 20 steps) to minimize errors of habituation and expectation [11]. The starting stimulus intensity for the descending staircase was determined by increasing the intensity from weaker to stronger and then reducing it to a comfortable level, as was shown in previous research to be effective [54]. The experiment uses a stimulus with $f_t = 30Hz$, carrier pulse width $T_c = 200\mu s$ and intensity steps of $0.1mA$, as used in previous experiments [54, 70, 53]. For each step, the stimulus is active for $100ms$, and a minimum stimulus onset asynchrony (SOA) of $2s$ was provided between steps. A total of 1600 data points was collected (20 points per staircase $\times$ 2 staircases $\times$ 4 taxels $\times$ 10 subjects). The threshold is calculated as the average of the last 10 points of reversals from each ladder. Participants wore a noise canceling headphone to avoid external noise affecting the results. The experiment took 30 minutes to complete.

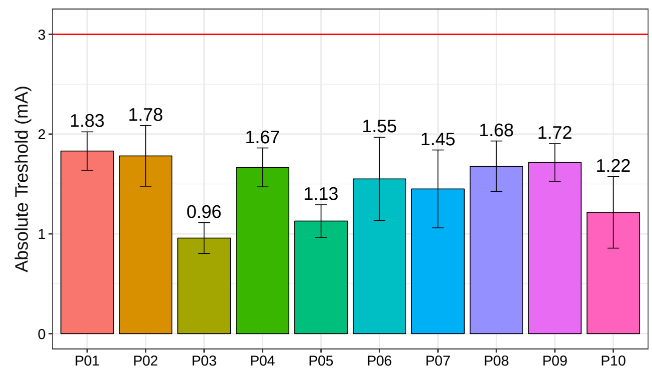

Figure 6. Absolute threshold per participant

Results

Figure 6 shows the absolute thresholds averaged over 4 taxels for each participant. They ranged from $0.96mA$ to $1.83mA$. These variations are in the range of previously reported electro-tactile thresholds. In Figure 6, the red line denotes the maximum stimulation intensity ($3mA$) supported by the Tacttoo wearable hardware. The highest absolute threshold recorded per electrode (P02 - $2.12mA$) is still eight standard deviations ($SD_{P02} = 0.11$) below this maximum. Hence, these results confirm that Tacttoo tattoos successfully deliver electro-tactile stimuli on the skin and our hardware setup is capable of reaching the required stimulation intensities.

After the experiment, we gathered qualitative feedback from participants. We asked them to comment on the experience of tactile sensation and comfort of wearing the tattoo on the skin. Participants generally commented that they could feel the sensation clearly, as also evidenced by the thresholds reported above. Furthermore, subjects stated the "sensation is very clear" (P01), "it was very comfortable" (P05) and "it felt like particles of sand" (P08). One user added "it felt like a sharp thing touching the finger, specially when strong" (P09). Regarding the Tacttoo as a skin overlay, subjects commented "it is thinner than latex gloves, I can feel even the skin texture on the surface" (P08) and "at some point, you do not feel it anymore, especially if there are no signals" (P09).

Feel-Through Characteristics of Tacttoo

In order to validate how well Tacttoo creates a *feel-through interface*, we investigated to what extent overlaying Tactoo on the skin degrades the natural tactile acuity. We selected the finger pad as the location for the test since it has the highest tactile acuity compared to other body locations [42] and it is commonly used in previous research for acuity tests [1, 44].

Participants

Ten participants (4 female, 1 left handed, aged 23 to 32) were recruited. None of them reported any health condition that might have affected their performance in this experiment.

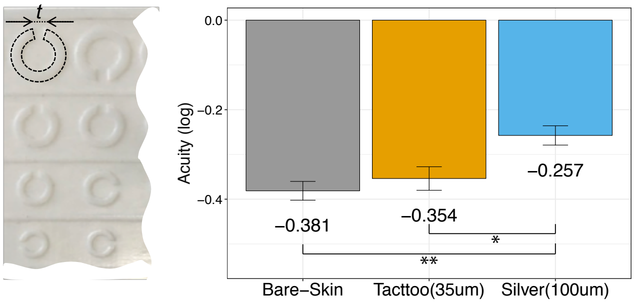

Figure 7. Ring chart used for acuity test and the results of the acuity test

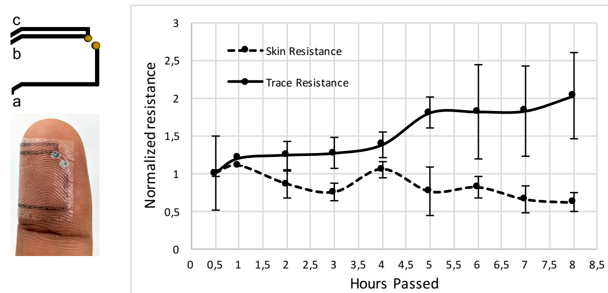

Figure 8. Durability test of Tacttoo. Overlay design (left) and normalized resistance over 8 hours (right)

Method

We tested the tactile acuity under 3 conditions: (C1) bare skin without any overlay for baseline comparison; (C2) a Tacttoo tattoo with max. $35\mu m$ thickness; and (C3) a slightly thicker rub-on tattoo with electro-tactile interface, approx. $100\mu m$, fabricated with silver conductive traces instead of PEDOT using the same functional design as in (C2). This third condition was selected to compare the slim Tacttoo design against the slimmest flexible electro-tactile displays in the literature, which are all above $100\mu m$ ($\sim 125\mu m$ [51], $\sim 200\mu m$ [61], $\sim 270\mu m$ [36]).

We have followed the methodology presented by Legge et al. [44] to measure tactile acuity on the fingertip using a chart of rings with an open gap (Figure 7, left). The chart consists of eleven rows. Each row has eight rings with a specific gap size (t in Figure 7, left) oriented pseudo-randomly in one of four directions. Gap sizes start from 4.8 mm (top row of the chart) and end at 0.55 mm (bottom row). Between rows, gap sizes are decreased in 0.1 log units. For the justification of selected dimensions and shapes, please refer to [44]. The experiment used three ring charts where the order of the rings in the chart is randomized. The order of charts and test conditions was counterbalanced to remove biasing and learning effects.

The experiment was conducted in a silent room. The participant was blindfolded and wore noise canceling headphones. Then participant was instructed to sequentially explore the ring chart with the dominant hand's index finger, starting from the top row, left to right, and for each ring state out loud the orientation of the gap. Allowed answers were: "up", "down", "left", "right" or "do not know". The number of errors was counted as the dependent variable. "Do not know" was counted as an error. Acuity is presented as a numeric test score and calculated similarly to [44] with the equation $Score = 0.6 + (ERRORS \times 0.0125)$, where $ERRORS$ is the number of errors, 0.6 is the lowest gap size, and 0.0125 is the gap size per ring $0.1/8$.

Results

Figure 7 right shows the comparison of results from the acuity test. The results for the bare skin condition are in line with the findings of Legge et al. [44]. The Tactoo interface decreased the acuity only slightly, whereas the thicker baseline tattoo resulted in a more considerable decrease.

Tukey multiple comparisons of means with Holm adjustment revealed a statistically significant difference between the conditions bare skin (C1) and thicker tattoo (C3) ($p < 0.01$) and between Tacttoo (C2) and thicker tattoo (C3) ($p < 0.05$). We did not find a statistically significant difference between bare skin (C1) and Tacttoo (C2).

These results demonstrate that Tacttoo has a minimal effect on tactile acuity and is successful at implementing a feel-through interface. These findings also show the strong effect of thickness on tactile acuity and underline the key importance of reducing the thickness to the level realized with Tacttoo. These findings are in line with results from the literature that revealed the strong difference in conformality of interfaces of $36\mu m$ vs. $100\mu m$ thickness [27].

Durability of Tacttoo

Tacttoo is designed to be applied on demanding body locations such as the fingertip that are subject to extensive external mechanical stresses. In consequence, the slim and flexible tattoo could be damaged or the electrical contact between skin and electrodes could break. We conducted a study to investigate the durability of 1) skin contact of electrodes and 2) te conductivity of connecting traces inside the tattoo during an 8 hour-long period while participants did their regular work activities in an office environment.

Participants

Five participants (aged 24 to 28) were recruited. They worked in an office environment and participated in the study while carrying out their everyday activities (i.e. document work, operating computers, telephones, etc.).

Method

To test at a demanding body location that undergoes external stresses, the Tacttoo was applied on the dominant hand's index finger. We designed a custom Tacttoo for resistance measurement. It uses the same materials, same substrate and the same design parameters as a normal Tacttoo. For resistance measurement, it contained two skin-exposed electrodes ($2mm$ diameter with $4mm$ spacing) and PEDOT:PSS connecting traces looped through the tattoo to terminal points. In the design (Figure 8 left), resistance measurement between terminals a and b measures the resistance across electrodes and skin (R^s) and b and c measures the conductivity of connecting traces (R^t).[6] We measured the two resistances at 30 minute intervals for the

[6] The trace resistances in a and b are less influential on R^s since R^s ranges in $100s$ of $k\Omega s$ while R^t in ranges in $10s$ of $k\Omega s$.

first hour and every hour afterwards for 8 hours using a Fluke 175 multimeter. Per participant, we recorded 18 values of resistances (R_1^s to R_9^s) and (R_1^t to R_9^t).

Results

Skin resistance is highly subjective to individuals and changes with time. Therefore, to visualize the long-term changes collectively, we normalized the resistance values read with the resistance read first. This resulted in a normalized array of resistances $\widehat{R}_i^x = R_i^x / R_1^x$ where $x = (s,t)$ and $i = 1,...,9$. Figure 8 shows the averaged normalized resistance changes for both skin and traces against time.

For 4 out of 5 participants, skin contact of all electrodes and conductivity of the connecting traces remained functional during the entire 8-hour period. One of the Tacttoos remained functional for only 7.5 hours when it accidentally got water spilled on it while the participant was washing hands. In general, trace resistance continued to increase with time and after 8 hours reached an average of 2.03 times the original value. However, since initial trace resistance is low enough ($18.4k\Omega, SD = 5.7$), even a greater than 2 times higher resistance is still within the bounds of stimulation range of the hardware controller. Measured skin resistance showed fluctuations around the initial value, but did not show an increasing trend similar to the traces.

Furthermore, qualitative feedback collected after the experiment showed participants did not feel wearing the prototype to be intrusive. For instance, they commented, "I could not feel the tattoo"(P4), "I was not conscious about it" (P2), "I was afraid I will break it, but it was stronger than it looked" (P1).

LIMITATIONS AND FUTURE WORK

The feel-through property of Tacttoo opens up new opportunities to combine real-world tactile stimuli with computer-generated stimulations. We have demonstrated first use cases of feel-through tactile output in this paper. However, the perceptual effects of simultaneous natural and virtual sensation remain underexplored. For instance, how does an overlaid virtual tactile stimulation affect or alter the natural perception? To what degree can both natural and virtual cues simultaneously deliver information to the skin? These questions need more psychophysical evaluations in future work and could lead to novel interactions.

While our hobbyist-level DIY screen-printing approach with commercially available functional inks does increase the accessibility of the technology for HCI researchers and interface designers, it entails some inherent limitations. The highest tactile density we used requires the connectivity layer to be routed with spacings as small as $0.5mm$. We observed that spacings below $0.5mm$ tend to increase the failure rates of the printed traces due to short circuits. We have successfully fabricated Tacttoo interfaces with 4 rows and 4 columns of electrodes, however, going beyond this will require routing with spacing lower than $0.5mm$. One solution is to decrease the trace width, but this results in a higher resistances. Another solution is to add multi-layered routing. However this affects the thickness of Tacttoo and may significantly affect the feel-through properties.

Our durability study shows promising results that Tacttoo can last for 8 hours in an office environment. One of the important limitations we identified is the damaging effects of water (notably, polymerization of the PEDOT:PSS conductor). Furthermore, after 2–3 hours passed in the study, we noticed the outer edges of Tacttoo showing slight effects of reduced skin contact. While these were not severe enough to interrupt the skin contact of the electrodes, it shows the effects of mechanical strain on the Tacttoo. Therefore a test under more demanding physical activities (e.g. use of power tools, sports activities) and for a duration longer than 8 hours is required to further evaluate the long-term durability.

In our current implementation, the Tacttoo interface prototype is tethered to a rigid control unit that is worn on the body, similar to the ones used in prior interactive tattoo prototypes [64, 46, 65]. Commercial implementations could scale down the size of this unit and eventually even might include it as a small rigid island on the tattoo itself. Furthermore, it seems promising to integrate additional input/output modalities beyond touch input, such as bend sensing, electro-physiological sensing, and visual output. This will further increase the richness of the interactive experience.

CONCLUSION

In this paper, we have contributed *Tacttoo*, a feel-through electro-tactile interface in a temporary tattoo form factor. Its very slim design, with less than $35\mu m$ thickness, supports conformal and ergonomic wearability on the user's skin and allows the user to feel natural tactile cues through the interface. This opens up new opportunities for tactile augmented reality, where real-world objects or tactile body landmarks are augmented with computer-generated tactile stimuli. We have presented an approach to design and fabricate customized Tacttoo interfaces using hobbyist-level screeen printing and commercially available inks. A new three-layer safety architecture ensures safe usage of the body-worn electro-tactile interface. Results from psychophysical studies and a technical user study have demonstrated that the system is functional, durable to last a workday and—most centrally—considerably improves over the state-of-the-art by being the first interface to retain natural tactile acuity similar to that of bare skin. In future work, we plan to further increase the resolution of Tacttoo interfaces. We also plan to combine Tacttoo tactile output with integrated multi-modal sensing and conduct further durability studies.

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