SkinMarks: Enabling Interactions on Body Landmarks Using Conformal Skin Electronics

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Figure 1: SkinMarks are conformal on-skin sensors and displays. They enable interaction on five types of body landmarks: (a) skeletal landmarks, (b) skin microstructures, (c) elastic landmarks, (d) visual skin landmarks, and (e) accessories.

ABSTRACT

The body provides many recognizable landmarks due to the underlying skeletal structure and variations in skin texture, elasticity, and color. The visual and spatial cues of such body landmarks can help in localizing on-body interfaces, guide input on the body, and allow for easy recall of mappings. Our main contribution are SkinMarks, *novel skin-worn I/O devices* for precisely localized input and output on fine body landmarks. SkinMarks comprise skin electronics on temporary rub-on tattoos. They conform to fine wrinkles and are compatible with strongly curved and elastic body locations. We identify *five types of body landmarks* and demonstrate novel interaction techniques that leverage SkinMarks' unique touch, squeeze and bend sensing with integrated visual output. Finally, we detail on the conformality and evaluate sub-millimeter electrodes for touch sensing. Taken together, SkinMarks expands the on-body interaction space to more detailed, highly curved and challenging areas on the body.

Author Keywords

On-body interaction; on-skin sensing; on-skin display; epidermal electronics; electronic tattoos; fabrication; flexible display.

ACM Classification Keywords

H.5.2. User Interfaces: Input devices and strategies, Interaction Styles, Haptic I/O

INTRODUCTION

The body is recognized as a promising input surface for mobile computing, as it offers a large and quickly accessible area for interaction. Prior research contributed input [11, 12, 14, 16, 17, 26, 27, 29, 41, 45] and output devices [11, 43] for on-body interactions. However, they mostly assume interactive elements to be rather large and only slightly curved.

The human body has various types of landmarks which are distinct from their surroundings. It offers unique possibilities for interaction due to their tactile properties and visual appearance. For example, protruding skeletal landmarks, like the knuckles, provide physical affordances for touching and circling around them. Prior work in human-computer interaction has briefly explored the potential of such unique landmarks. Gustafson et al. [8, 9], for example, suggested using the segments of the finger as distinct input buttons. However, thus far, the majority of potentially beneficial landmarks remain unexplored and unsupported. These include landmarks with highly curved geometries, tactile microstructures, or strong deformability.

This paper presents *SkinMarks*, an enabling technology for interaction on body landmarks. SkinMarks are highly conformal interactive tattoos, which enable precisely localized input and output on five types of body landmarks.

SkinMarks are inspired by recent research on slim, skin-worn sensors and displays [41, 17, 27, 43]. We extend beyond prior work by contributing highly conformal skin electronics with co-located input and output, which are compatible with strongly curved, elastic, and tiny body landmarks. These make it possible to use the plethora of tactile and visual cues on body landmarks for direct, eyes-free, and expressive interaction.

The contributions of this paper are:

- We introduce SkinMarks, novel skin-worn I/O devices with co-located input and output, which are enabled through highly conformal and precisely localized skin electronics.

- We describe a SkinMarks implementation based on temporary rub-on tattoos. It allows for custom-shaped, slim, and stretchable devices that conform to fine body landmarks.

- We identify five types of body landmarks for on-body interaction. They are informed by anatomy, skin properties, and body-worn accessories.

- We demonstrate interaction techniques on body landmarks that leverage SkinMarks' unique touch, squeeze and bend sensing with integrated visual output.

- We present results from technical evaluations and user studies that validate conformity (4 µm to 46 µm thin), precise localization, and touch input on sub-millimeter electrodes.

In summary, SkinMarks is an enabling technology for interactions on body landmarks. The highly conformal skin-worn electronics support precisely localized interactions. They expand the on-body interaction space to more detailed, highly curved, and challenging areas of the body. These advances enable novel interactions on body landmarks, which we will demonstrate in this paper.

RELATED WORK

On-body interaction uses the body as an input surface for always-available input and output in mobile computing. It has been investigated for many body parts, such as, the palm [5, 8, 9, 38, 39], fingers [2, 8, 14, 44], nails [16], arms [12, 24], back of the hand [23], and ears [26].

On-body interaction can involve various aspects of input sensing (such as touch, shear and bend sensing) as well as visual output on the body. Various approaches for input sensing have been investigated. Camera-based sensing, with RGB cameras [28, 37] or depth cameras [5, 11], allows direct input on large areas of the body, but requires line-of-sight to the camera and is susceptible to lighting conditions. Sensors injecting a signal into the body, e.g. bio-acoustic sensors [12] and electromagnetic waves [45] allow for touch and gesture sensing, work on many body locations and do not require a skin overlay. They, however, suffer from low spatial resolution and are limited to single-touch. Magnetic sensing [2, 14] employs magnets and Hall effect sensor grids, which allow for high resolution sensing on small parts of the body. They require augmenting the finger with a magnet and can only sense its position, but not robustly determine surface contact. Photo-reflective sensing [29] recognizes deformations of the skin, e.g. shear, pressure and squeeze. This recognizes the many input modalities beyond touch that can be performed on the skin [42]. Radar-based sensing [22] enables motion, range, and velocity sensing, but makes tracking of spatial configurations difficult. Another approach are on-skin electronics, which form the foundation of SkinMarks. These electronics are placed directly on the skin, thereby enabling direct input and output on the skin.

Landmarks on the body have a long tradition of use in various disciplines, including medical sciences, anthropology, and fine arts. In these contexts, a landmarks mainly act as unique and unambiguous references on or inside the body, e.g., to locate points and areas of interest, to compare biological shapes, or to measure anatomy. In visual arts, for example, body landmarks help artists find forms and assess body proportions. In contrast, in anatomical sciences, landmarks are defined as *structurally consistent loci which can have evolutionary, ontogenic, and/or functional significance, and must be consistently present on all forms under consideration in order to be useful in analysis* [21].

Prior HCI research has shown initial empirical validation that skeletal landmarks can improve interaction. Gustafson et al. show that the tactile features and natural divisions of finger and their segments allow for localization of UI elements in four-column layouts [8] and that palm-based interfaces remain usable when operated eyes-free, due to the tactile cues of the palm [9]. Dezfuli et al. [5] distinguish nine coarse landmarks on palm and fingers. Wang et al. [38] proposed using the joints between the finger segments to distinguish between five discreet buttons per finger. Also the fingertip can be used as a well-distinguishable landmark [30]. In this work, we enable landmark interactions on a considerably wider range of landmark types, by supporting input and output on highly curved geometries (e.g. knuckles), tactile skin microstructures, and landmarks with strong deformability.

We base our SkinMark implementation on the emerging stream of skin electronics and epidermal electronics [18, 10, 15, 40, 19]. These enable skin to become an interactive surface for human-computer interaction [36]. iSkin [41] introduced thin and stretchable skin overlays that capture touch and pressure input for mobile computing. These sensors are made of bio-compatible and stretchable PDMS. Using digital fabrication, they can be customized in size, shape and visual appearance. Stretchis [43] added output with stretchable electroluminescent displays by extending the PrintScreen approach [31]. Skintillates [27] achieved considerably slimmer on-skin touch and bend sensors by screen printing conductive traces on temporary rub-on tattoos. Output was realized with conventional LEDs. DuoSkin [17] uses gold leaf as a conductor and includes touch interaction, NFC communication and thermochromic visual output. Compared with interactive textiles [33], these interfaces conform more closely to skin.

This paper extends beyond this prior work in two ways, to enable interactions on body landmarks: First, we contribute sensors and displays that are compatible with strong curvature, deformation, and strain, which all are inherent to landmarks. Second, we enable sensing on fine and narrow areas of landmarks (e.g. flexure lines). Compared to PDMS-based electronics which are more than ≥ 200 µm thick [41, 43]), our fabricated touch sensors (4 µm) and EL displays (31 µm to 46 µm) are considerably thinner and hence allow for higher conformality to the body. In contrast to Skintillates and DuoSkin, which investigated geometries of lower curvature at the wrist (≈ 26 mm), our sensors support non-developable surfaces with small radii, such as the knuckles (≈ 8 mm). Further-

more, compared to all prior technologies, SkinMarks support touch electrodes that are a magnitude smaller (≤1 mm) than those of prior work (≥8 mm) [17, 27, 41]. This enables interaction on five types of body landmarks, which we introduce in the following section.

LANDMARKS FOR ON-BODY INTERACTION

In the context of HCI, body landmarks have *interactional significance*. Their main purpose is to support and ease on-body interaction. We define body landmarks as follows:

Body landmarks are locations on the body, which are *tactually or visually distinct* from the surroundings.

Body landmarks can be *generic* for all users and *permanent*, similar to landmark definitions in anatomy. However, they can also be *personal* or *temporary*.

Benefits for On-body Interaction

Localization. They help users localize interactive elements on the body by leveraging human sensory and motor capabilities: (1) Proprioception allows for coarse, eyes-free landmark localization. (2) Visual feedback allows for precise adjustments while reaching the body. (3) During the touch, tactile feedback allows for eyes-free adjustments, through the tactile sensation of the touched and of the touching surface.

Guidance. They provide affordances that inform how to interact, and also guide user input. For instance, a flexure line affords linear sliding while the soft webbing in-between fingers affords continuous pressure or stretch input.

Recall. If appropriately chosen, they can help users memorize mappings between body locations and interactive functionality. A landmark can act as a simple visual or haptic cue that reminds the user about the presence of an input widget on her body. Landmarks can also draw upon semantic associations with specific loci on the body.

Types of Body Landmarks

Based on the aforementioned definition of body landmarks, we identified five main types of landmarks that are derived from human anatomy [6] and body adornments [4]:

Skeletal Landmarks. Skeletal landmarks are created by bones and joints in the body, resulting in curved surface geometries. These can be felt by the interacting finger and guide or constrain tactile input on the body, even during eyes-free input. Pioneering research has investigated how finger segments, fingertips and segments of the palm can guide on-skin interaction [5, 8, 9, 30, 38]. Yet, the body offers a much wider variety of skeletal landmarks. For example, the highly curved geometry of a protruding knuckle affords touch contact, while a straight finger affords linear sliding movements. Moving beyond static landmarks, some skeletal landmarks allow for *dynamic* poses. For example, a straight hand has a relatively flat and even surface along the knuckles, which affords linear sliding motions. It can be dynamically transformed to a highly curved area when forming a fist, with four knuckles clearly protruding; this affords interaction on discrete areas.

In addition to skeletal anatomy, the properties of skin allow for additional, previously unexplored, types of landmarks:

Skin Microstructure Landmarks. The fine tactile texture of skin can largely vary, e.g., due to flexure lines, wrinkles, and hair follicles. These tactile cues can be felt by the interacting fingertip. This can generate tiny and fine landmarks that allow for highly localized on-skin interactions.

Elastic Landmarks. The elasticity of skin varies across body locations, depending on the amount of elastin in the dermis layer [20]. For example, a webbing has a considerably higher elasticity than its surrounding. These soft landmarks afford localized skin deformations, such as shearing, stretching, and squeezing, for continuous and expressive on-body input.

Visual Skin Landmarks. Skin varies in its pigmentation and therefore offers landmarks that stand out by their visual properties. For example, birthmarks can form clearly articulated visual entities. These landmarks are highly personal and differ in their occurrence and location across users. Their visual cues support spatial mappings, provide cues for localization, and their shapes afford different touch interactions.

Landmarks of these four types can occur naturally on the body. However, such landmarks could also be actively added or modified by the user, e.g., through make-up, tattoos, or even implants. In addition to these body-intrinsic landmarks, external objects that are worn on the body can create temporary and removable landmarks:

Accessory Landmarks. Body-worn accessories, such as rings, bracelets, earrings, or wristwatches, provide tactile and visual cues on the body. As such, they can function as a temporary, user-generated body landmark. They can be easily located on the body and can offer distinct physical affordances for interaction; e.g., a ring can be touched and rotated [1].

IMPLEMENTATION OF SKINMARKS

Body landmarks create a demanding set of challenges for the implementation of input and output surfaces: First, on-skin electronics must be *conformal* on landmarks, despite their highly curved geometries and extensive skin deformation. Second, interaction with on-skin electronics must be *precisely localized* to allow for interaction on body landmarks that can be small and of irregular geometry.

This section presents the implementation of SkinMarks interactive tattoos, which enable interaction on body landmarks. We start by providing an overview of our fabrication approach. Then we detail on our technical contributions to make SkinMarks conformal on challenging geometries. Finally, we describe the implementation of precisely localized, co-located input and output surfaces for sensing of touch, bend and squeeze input and for visual display.

Fabrication: Multi-layer Functional Inks on Tattoo Paper

Body landmarks can vary greatly for an individual user and between users. We base our implementation of SkinMarks on screen-printed electronics, because it is a flexible method to create small volumes of thin-film sensors and displays that feature a custom shape and a high print resolution [31].

To fabricate an interactive tattoo, we use commercially available temporary tattoo paper (Tattoo Decal Paper) as the substrate, as proposed in recent work [17, 27]. We screen print one or multiple layers of functional inks onto it. After printing each layer, the ink is heat cured with a heat gun (130°C, 3 minutes). After adding a thin adhesive layer, the tattoo is ready to be transferred onto skin.

SkinMarks are powered and controlled using an Arduino microcontroller. We recommend to place the microcontroller at a body location which offers enough space and undergoes little mechanical strain, for instance the wrist. For connecting the tattoo with this location, we extend the tattoo by printed conductive traces that each end with a printed connector surface in close proximity to the microcontroller. We solder a conventional wire onto copper tape and adhere the tape to the isolation layer, under the printed connector.

Conformal Interactive Tattoos: Slim and Stretchable

To ensure that an interactive tattoo is conformal on challenging landmark geometries and robust to stretching, we set out to minimize the thickness of printed functional layers (as suggested in [15]) and to use intrinsically stretchable materials.

Layer thickness is mainly influenced by two factors: screen density and ink viscosity. We minimized the layer thickness by printing with a dense screen (140TT). We further reduced the thickness of conductive structures by printing a conducting polymer (PEDOT:PSS translucent conductor, Gwent C2100629D1, 500-700 Ω/sq). Compared to silver ink, which was used in prior work [27], the ink is less viscous and results in considerably thinner layers. The thickness of a screen-printed layer of PEDOT:PSS conductor is approximately 1 μm, a magnitude slimmer than screen-printed silver in prior work (≈16 μm [27]). A tattoo with a touch sensor measures approximately 4 μm. A tattoo with visual output measures 31 μm to 46 μm, including the tattoo paper. This allows us to introduce temporary tattoos for tactile user input and visual output on highly challenging locations, such as the knuckles.

PEDOT:PSS conducting polymer has an additional important advantage over conductors made of metal, such as silver ink [17] or gold leaf [27]: it is intrinsically stretchable [25]. This does not only make the conductor conform better to challenging geometries; it also makes it considerably more robust to mechanical strain [25]. To further improve the robustness, we recommend laying out conductors in a horse-shoe pattern [13] in locations that are subject to extensive strain (e.g., knuckles, webbing, or wrist) or route traces around such areas, if possible.

Based on these principles, we show conformal touch, bend and squeeze sensors and conformal EL displays that allow for interaction on body landmarks (see Figure 2).

Touch Sensing

Touch has been identified as an important input modality for on-skin electronics [41, 27, 17]. Solutions from prior work used fingertip-sized electrodes [41, 27, 17]. Body landmarks
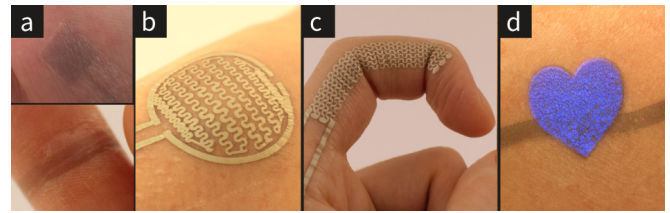

Figure 2: SkinMarks supports: (a) capacitive touch buttons and sliders, (b) squeeze sensors, (c) bend sensors, and (d) electroluminescent displays.

require smaller electrodes for precisely localized interaction on the landmark, e.g. flexure lines.

We use capacitive loading mode sensing (single capacitance) to measure touch contact and sliding (Figure 2a). The touch-sensitive electrodes are printed with one conductive layer of PEDOT:PSS and are connected to a commercial capacitive touch controller (Adafruit MPR121). Each tattoo can contain one or multiple custom-shaped electrodes, which can be printed in close proximity to each other. They support interpolation and allow for slider sensor designs [3].

Our evaluation of touch sensors shows that SkinMarks allows for electrodes with a width of 0.25 mm and hence supports small landmarks. This is by an order of magnitude smaller than prior on-skin touch sensors [17, 27, 41].

Squeeze and Bend Sensing

Skin allows for deformation input as a a further modality for tactile on-body interactions, as recommended in [42]. Deformation interaction can be used on various landmarks, but is especially interesting for elastic landmarks to leverage their intrinsic deformability.

We present an embedded sensor for capturing *squeeze input* on skin, based on a printed strain gauge. Squeezing deforms the skin and results in compressive strain on the strain gauge. We found that the intrinsic stretchability of PEDOT:PSS prevents the strain gauge from giving precise readings. Therefore, we use silver ink (Flexible Silver Ink, Gwent C2131014D3). However, our initial tests showed that the brittle silver tends to break easily. To increase the robustness for high-stress areas on the body, we cover the silver pattern with a second layer of PEDOT:PSS containing the exact same pattern. This allows the strain gauge to remain functional, even when the silver connection breaks at a few locations, because the second layer bridges the breaks.

We implemented two squeeze sensor designs. They have a trace width of 0.75 mm. The larger one, designed for the forearm, has a dimension of 60×21 mm with 13 parallel lines laid out in a horse-shoe pattern. The smaller one (Figure 2b) was designed for the head of the ulna, is dimensioned 21×21 mm and features 9 parallel lines.

We evaluated the robustness of squeeze input by measuring the signal to noise ratio [3]. For a sample with a dimension of 60x21 mm, we calculated the average SNR of six squeeze sensors. They were deployed on six locations on the upper limb of five participants, chosen to cover a wide range of skinfolds

(2–23mm; measured with an EagleFit Slim Guide Caliper). Each sensor was squeezed 20 times. The squeeze sensors achieved an average SNR of 17.0 (SD=7.97).

Furthermore, SkinMarks supports *bend sensing*, similar to prior work [27]. We use this principle to detect dynamic pose-changes of skeletal landmarks to allow for dynamic interface elements. The bend sensor on the finger measures 72x8 mm and features 6 parallel lines with the horseshoe pattern. Again, the additional layer of PEDOT:PSS prevents the strain gauge from breaking in case of tiny cracks in the silver layer. We show this principle on the finger (see Figure 2c).

Conformal Touch-sensitive Displays

We contribute tattoo-embedded active displays to allow for custom-shaped, co-located input and visual output on SkinMarks. Our displays have a faster response time than thermochromic displays [17] and are considerably slimmer than prior body-worn LEDs [27] and EL displays [43]. They are thin and robust enough to conform to challenging geometric landmarks, such as knuckles or the flexure lines of the palm. The overall thickness of the display is between 31 μm to 46 μm. It is deformable and captures touch input (see Figure 1c, 2d, and 4).

We base our implementation on electroluminescent (EL) displays, which feature high update rates and energy-efficiency. The implementation follows the basic principle introduced by PrintScreen [31]. In contrast, our displays use two electrodes made of PEDOT-based translucent conductor. As discussed earlier, this allows for thinner and more robust layers. Between the electrodes is one layer of phosphor paste that determines the color of the display. We further reduce the thickness of the display by replacing the dielectric paste used in prior work by a transparent resin binder (Gwent R2070613P2). The resin binder is used as a dielectric and allows for printing thinner layers. Furthermore, it is completely transparent to avoid visible margins, as presented in prior work [31]. The EL display is driven with a Rogers D355B Electroluminescent Lamp Driver IC (145 V; max. 1 mA). It allows for integrated touch sensing by time-multiplexing a display cycle and a capacitive sensing cycle, as introduced in previous work [31].

INTERACTION ON BODY LANDMARKS

SkinMarks enable new forms of on-body interaction. We present novel interaction techniques for the five types of body landmarks: skeletal, skin microstructure, elastic, visual skin, and accessory landmarks.

Tactile Cues on Skeletal Landmarks

The high curvature of skeletal landmarks creates distinct tactile and visual cues, which support on-body interaction in various ways. For one, cues can help the user to memorize mappings; for instance, the user can associate an input element with a specific knuckle. Second, cues can also help localize the input element while looking at it or feeling the geometry through the touching finger. In addition, different geometries afford for different interactions. Last but not least, unique geometries can also be formed by a group of multiple adjacent landmarks, such as the four knuckles of a hand.
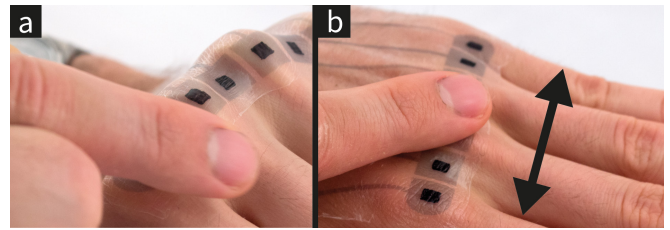

Figure 3: Interaction on challenging, highly curved skeletal landmarks: (a) tapping the peaks and valleys for discrete input; (b) sliding along the knuckles for continuous input.

We demonstrate these benefits for on-body interaction by deploying a touch-sensitive SkinMark sensor on the knuckles (Figure 3). SkinMarks allow for input on the knuckles (knuckle peaks) and around the knuckles (knuckle valleys), both areas with a high curvature. These can be used to distinguish multiple different input elements that are associated with either a valley or a peak. We demonstrate that the knuckles can be used as discreet touch elements (fist) or as a slider that provide small tactile ticks (flat hand).

Dynamic Interface Elements using Pose-based Input

Body movement allows for dynamic interface elements using pose-based input on skeletal body landmarks. The ability to change the pose on demand enables various novel interactions. For instance, when the user is making a fist the knuckles have a high curvature, clearly exposing the knuckle peaks. This allows for precisely locating discrete touch buttons. In contrast, while doing a flat hand, the knuckles form a relatively flat surface, which allows for continuous sliding (see Figure 3).

SkinMarks can capture the current body pose and change the interface dynamically. To illustrate this, we implemented a music player control, which is worn on the side of the index finger (Figure 4). It contains a printed bend sensor overlaid with touch-sensitive display elements. Those elements change their functionality based on the pose of the finger. When the index finger is straight, it affords continuous and linear movement along the finger (Figure 4a). It then acts as a volume slider. When it is bent, the flexure lines at the joints become more prominent; they visually and tactually split the input area into three distinct areas (Figure 4b).
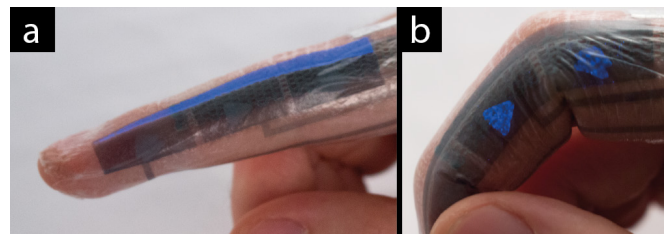

Figure 4: Using body posture to dynamically change functionality: (a) Straight finger for linear movements, e.g. to control volume, (b) bent finger for discrete touch areas.

These afford discrete touch input. Therefore, when bent, the interface switches to three discrete buttons for play/pause, next song and previous song. The integrated displays show which mode is active, either by illuminating the buttons or the slider. Switching between these modes is fast, easy and discreet to perform.

Precise Touch Input on Skin Microstructure Landmarks

Body landmarks can be small and still very beneficial for on-body interaction. Our temporary tattoos allow for precise application on the landmark and for precise touch elements. This allows for sensing touch input exactly on the location of a tiny landmark to use its tactile properties.

We demonstrate this with a new interaction technique that makes use of tactile skin surface-structure: The Wrinkle Slide interaction technique. A touch sensor augments one or multiple flexure lines (the larger wrinkles) on a finger. By *sliding along* the flexure line, the user can continuously adjust a value. A selection can be made by tapping. The precise tactile cues of the flexure line allow for tactile localization and guide the user during sliding, without requiring visual attention. The technique also allows for one-handed input using the thumb of the same hand (thumb-to-finger input). Therefore, it can support interactions in busy mobile scenarios, e.g., while running. We demonstrate its use as a one-handed remote to control the volume of a mobile music player.

The wrinkle slider contains two triangular printed electrodes, which together measure 30×4.5 mm (Figure 5a). They are used for capacitive touch sensing. Interpolation allows to capture the touch location on the slider. SkinMarks are thin enough to closely conform to flexure lines and allow feeling of the wrinkle through the sensor tattoo.

A similar sensor design allows for toggle input (Figure 5b). The user switches the toggle on or off by *sliding across* a flexure line. The tactile feedback provides interactional awareness to the user. The input is sensed with two parallel slim electrodes. The temporal signature in their touch response determines the direction of the slide. The input can be mapped to opposed commands, e.g. to accept or decline calls.
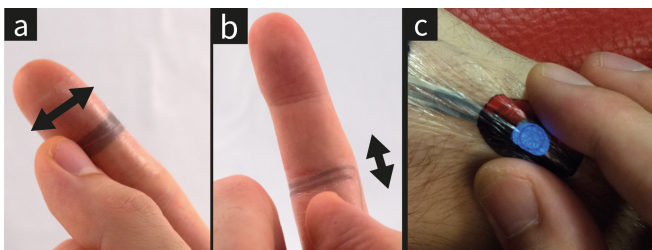
Figure 5: SkinMarks allow for precise touch input on skin microstructures: (a) wrinkle slider and (b) wrinkle toggle. (c) Interacting on an elastic landmark.

Expressive Deformation Input on Elastic Landmarks

Localized deformation input enriches the input vocabulary of landmarks. For example, an interface can distinguish between touch input and squeeze input to trigger different commands.

We demonstrate deformation input on the circular protrusion on the wrist created by the head of the ulna bone. This location is easily localizable through its visual and tactile cues. We implemented a *CaptureMark* (Figure 5c). The Capture-Mark is a circular ball for capturing virtual objects in augmented reality games, e.g. treasures or Pokémon. The user is notified about virtual objects with an audio feedback. The user can attempt catching it by squeezing the tattoo. Afterwards, the CaptureMark blinks and finally lights up for a few seconds to notify the user that the virtual object is caught.

Dynamic Visual Cues on Visual Skin Landmarks

Visual landmarks on the skin can be leveraged to provide personalized and dynamic visual cues for on-body interaction. To illustrate this type of landmark interaction, we have implement a *HeartMark* (Figure 6b), a touch-sensitive heart-shaped display to augment a birthmark. The HeartMark notifies the user about the availability of a loved one. Touching it starts a call with that person.
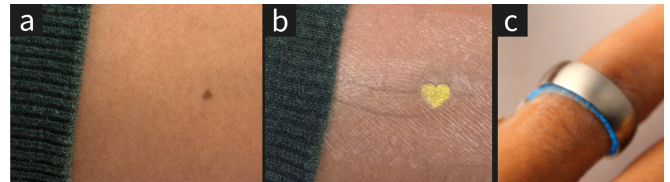
Figure 6: SkinMarks can augment visual skin landmarks, e.g. birthmarks (a–b), and passive accessories, e.g. a ring (c).

Interaction on Passive Accessories

Body-worn passive accessories can function as a landmark for interaction, given that they provide unique tactile and visual cues. Although accessories are widely used, they have not been integrated with on-body electronics. SkinMarks enable interaction with passive objects in two ways: First, it enables skin illumination under and around the object using on-body displays, similar to ScatterWatch [32]. Second, it can make accessories touch-sensitive, through capacitance tags [34]. Touch sensing requires the accessory to be conductive; this holds true for a wide variety of jewelry and other accessories. Neither interaction require modification of the passive accessory.

We implemented an augmentation for a wedding ring (Figure 6c), to allow for subtle communication between both partners. Touching the ring creates a glow around the partner's ring. This is made possible by affixing an interactive tattoo at the finger segment where the ring is worn. The tattoo contains a non-exposed conductor which lies under the ring and capacitively couples with it for touch sensing. Moreover, it contains a visual display that slightly extends beyond the ring, for on-demand illumination.

TECHNICAL EVALUATION

This section presents results from technical experiments that investigate the two key technical contributions of SkinMarks: First, do SkinMarks support interaction on challenging landmarks by *conforming to skin* despite high curvatures and strong elasticity? Second, do SkinMarks allow for *precisely localized interaction* on fine landmarks?
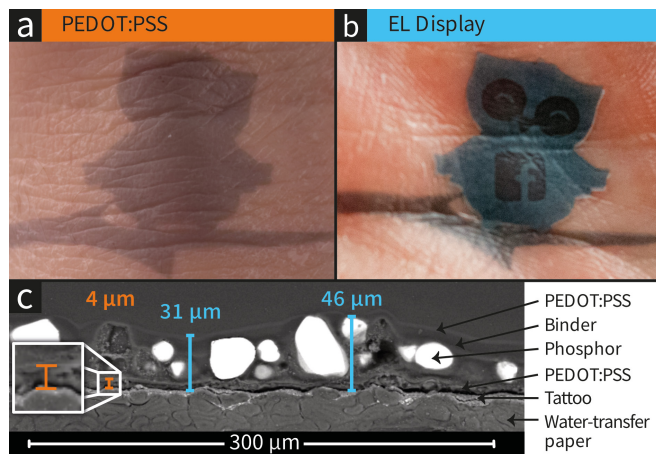
Figure 7: SkinMarks conform to wrinkles: (a) a tattoo with PEDOT:PSS conductor; (b) tattoo with EL display. (c) Cross-section of a tattoo with printed EL display, taken with a scanning electron microscope (SEM).

Conformal Form Factor

We investigated the two main factors for conformal electronics: thickness and stretchability.

To investigate the layer thickness of printed inks on a Skin-Mark, we analyzed cross-sections of printed SkinMark tattoos on the water-transfer paper with a Scanning Electron Microscope (SEM). Figure 7 shows the various layers of inks. A layer of PEDOT:PSS layers is approximately $1\,\mu m$ thick ($\approx 4\,\mu m$ with tattoo paper). A full TFEL display is between $31\,\mu m$ to $46\,\mu m$ thick (Figure 7c). These numbers demonstrate the vastly reduced display thickness compared to prior interactive tattoos [17, 27] and TFEL displays [31, 43]. Figure 7 a&b illustrate how SkinMark tattoos closely conform to wrinkles. Our results confirm prior research of Jeong et al. [15], which show that elastomer membranes of $5\,\mu m$ have excellent conformality even to small wrinkles, while membranes of $36\,\mu m$ have good conformality on larger wrinkles (e.g. flexure lines).

Our experiments showed that the stretchability of the tattoo substrate ranges between 25–30%. PEDOT:PSS retains conductivity up to 188% strain and is reversibly stretchable up to 30% strain [25]. For comparison, the stretchability of the human epidermis is around 20% [35]. The combination of both makes SkinMarks intrinsically stretchable and more robust against strain than metals (e.g. [17, 27]).

Precise Localization: Touch Input and Tattoo Application

We validate the two necessary conditions for precisely localized input. First, can touch input be accurately sensed on sub-millimeter electrodes? Second, are users able to apply tattoos with a high spatial accuracy on the landmarks?

Touch Input on Sub-Millimeter Electrodes

Methodology. We recruited 12 voluntary participants (2 female, 22–32 years, mean 26.8 years). Electrodes of different widths (1.0, 0.75, 0.5, and 0.25mm) were screen printed with PEDOT:PSS on tattoo paper and applied to the flexure line of the index finger of the non-dominant hand. The participants
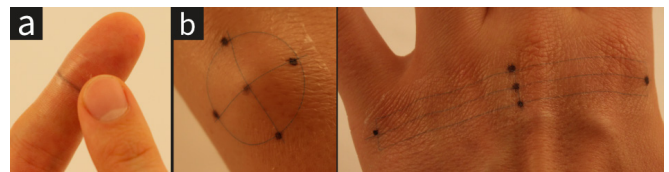

Figure 8: Study setup: (a) evaluation of touch on sub-millimeter electrodes and (b) of precise tattoo application.

were asked to touch each line 30 times for 2 seconds to collect enough data points in the touched and non-touched state. Participants could freely choose how they touch the tattoo. The electrodes were connected to a commercial capacitive touch controller (Adafruit MPR121). This interfaced with an Arduino, which was using a serial connection to a PC for data logging. Each session took approximately 25 minutes, including 5 minutes of training.

Results. We measured the signal to noise ratio (SNR) of capacitive sensing for each line width. For 1 mm, the average SNR was 56.3 (SD=20.9). It was 41.2 (SD=16.4) for 0.75 mm width and 20.1 (SD=9.5) for 0.5 mm width. For the smallest electrode of 0.25 mm, the average SNR was 13.1 (SD=5.5). For each single data point, the SNR was above 7.0, which is the required SNR for robust touch sensing [3].

Precise Application of SkinMarks Tattoos

Applying temporary rub-on tattoos on planar areas is a straightforward task, but precise alignment on curved landmarks can be more challenging. Hence, the second key requirement for precise and accurate interaction on body landmarks is that the user can apply the interactive rub-on tattoo on skin with a high degree of spatial accuracy.

Methodology. We recruited six voluntary participants (1 female, 25–28 years, mean age 26.3 years). Each participant had to precisely apply four substrates of tattoo paper at four challenging locations: knuckles (skeletal landmark), head of ulna (skeletal landmark), flexure lines on the finger (skin microstructure landmark), and birthmark (visual skin landmark). The order of presentation of tattoos was counter-balanced. The tattoos had fine target points (see Figure 8). The participants had to align these target lines precisely with the target points that the experimenter had marked on the participant's skin. For the birthmark, the participants were free to choose any location on the forearm. We instructed the participants how to apply a temporary rub-on tattoo, before letting them apply all four tattoos on their own. We took visual surface scans to measure the error offset for each of the tattoo locations. Each session took approximately 30 minutes.

Results. The results show an inherent ability of users to apply tattoos with a millimeter or even sub-millimeter accuracy at challenging landmarks. The mean error of placement was below $1.0\,mm$ for all locations. Most precise were birthmark (mean=0.16 mm, max=1.0 mm) and flexure line (mean=0.26 mm, max=0.7 mm), followed by knuckles (mean=0.84 mm, max=1.8 mm) and the head of ulna (mean=0.74 mm, max=2.2 mm).

DISCUSSION, LIMITATIONS, AND FUTURE WORK

This section discusses practical insights, limitations, and lessons we have learned during the nine-month-long design and implementation of several iterations of prototypes.

Printing and Fabrication. Each tattoo is personalized and individually fabricated. In our experiments, fabrication of a functional tattoo required between 3–3.5 hours. Preparing the screen printing mask took the longest time ($\approx$ 2.5 h). One mask can, however, contain designs for multiple tattoo prints. The actual printing and curing is fast for touch sensor tattoos ($\approx$ 5 min) and takes between 30–60 minutes for fabricating all layers of a display tattoo. These manual steps can be largely automated using high-end industrial screen printing tools. We envision that in the near-term future a personalized interactive tattoo can be printed in less than a minute on a desktop printer.

Connector and Power. During prototyping, we found that the connector is the weakest element in the chain. This is because the connection between printed conductors, which are slim and flexible, and external conductors, which tend to be much thicker and more rigid, is subject to strong mechanical forces. Our final solution connects each connection pad on the tattoo with a slim connector made of flexible copper tape ($\approx 30\,\mu$m). Applying the adhesive layer to the entire tattoo, except the connectors, helps to ensure proper connection. Aligning the tattoo on the connector can be eased by visually marking the connector areas on the backside of water-transfer tattoo paper. Future prototypes would benefit from further miniaturizing of the technology to enable a complete system within the tattoo layers. As a first step, miniaturized rigid microcontrollers (e.g., Intel Curie) could be combined with flexible batteries to enable capable, yet less flexible, areas, with on-skin advanced computation and control. Alternatively, the use of RFID/NFC [19, 17] could enable remote powering of basic sensors and allow communication through modulated backscatter. Other approaches include power harvesting of thermal energy or motion using piezoelectronics, where the limited efficiency and bandwidth might still be sufficient for certain types of sensing and transmission.

Safety. Electroluminescent displays are driven using high-voltage, but low-current AC [31]. We recommend using a current-limiter circuit. We found that the adhesion layer does not guarantee sufficient insulation of the current of electroluminescent (EL) displays from the skin. We recommend two additional layers of rub-on tattoo under SkinMarks to ensure proper electrical isolation (each layer is $\approx 3\,\mu$m). This approach also ensures that ink does not contact the user's skin. According to prior work [7], PEDOT:PSS does not cause skin irritations and has no long-term toxicity under direct contact.

Tattoo Application. For close conformality on body landmarks that allow for dynamic pose-changes, e.g. knuckles, we recommend to apply the temporary tattoo in the flat pose. Otherwise the tattoo application requires more attention to avoid gaps at retracted locations, where the tattoo might not touch the skin. We also found that tattoos covering larger area (>5 cm in one dimension) are challenging to apply on landmarks with high curvatures, because the water-transfer paper is relatively stiff before application. If possible, we recom-

mend having multiple smaller tattoos covering the same area. For example, the electrodes and wires can be divided into individual tattoos for each knuckle and aligned separately.

Unintentional input is one of the open issues in on-body interaction. From our experience we noticed that protruding landmarks and the inner areas of the palm are more susceptible to unintentional input when compared to other locations. Landmarks located at locations that retract, such as the area in-between the knuckles, seem promising to reduce the likelihood of unintentional input. Another approach consists of using more expressive gestures that are more robust by design, such as the presented directional toggle gesture or squeeze-based input.

Additional Landmarks. While the five types of landmarks introduced in this paper cover a wide range of scenarios and interactions, there remain more landmarks to be investigated. This includes even finer skin microstructures (like hair), artificial visual skin texture (like permanent tattoos, tan lines, and henna art), and a wider range of accessories (including earrings and piercings). Other skin properties, e.g., the distribution of cutaneous receptors, could also be beneficial for on-body interaction and should be investigated in future work.

Empirical Investigations. This work contributed toward enabling interaction on body landmarks. Additionally, we plan to explore and quantify the benefits of body landmarks for on-skin interactions through empirical investigations. Future work should also study SkinMarks in longitudinal user experiments to see how SkinMarks can fit in users' everyday routines.

CONCLUSIONS

We have introduced *SkinMarks*, a technical enabler for interaction on small, highly curved, and deformable body landmarks. It expands the on-body interaction space toward more detailed interaction on challenging body areas. SkinMarks are temporary interactive tattoos. They sense touch on submillimeter electrodes, capture squeeze and bend input, and support active visual output. Through a vastly reduced tattoo thickness and increased stretchability, a SkinMark is sufficiently thin and flexible to conform to irregular geometry, like flexure lines and protruding bones, while still allowing the user to reference those landmarks tactually or visually. We introduced five types of body landmarks that are supported by our technology. We demonstrated novel interactions on each of these landmarks to advance on-body interaction towards more detailed, highly curved and challenging body locations.

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