iSkin: Flexible, Stretchable and Visually Customizable On-Body Touch Sensors for Mobile Computing

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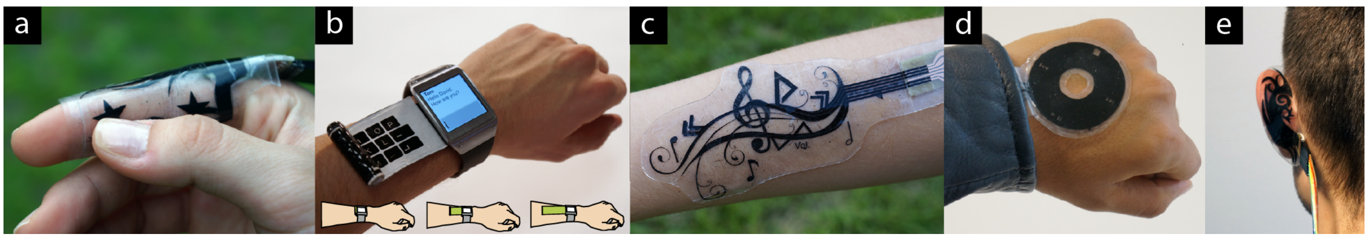

Figure 1. iSkin is a thin, flexible, stretchable and visually customizable touch sensor that can be worn directly on the skin. We present three novel classes of on-body devices based on iSkin: (a) *FingerStrap*, exemplified here with a strap on the index finger for fast, one-handed control of incoming calls; (b) *Extensions for wearable devices*, exemplified here with a rollout keyboard attached to a smart watch; and *SkinStickers*, exemplified here with (c) an input surface for a music player attached to the forearm, (d) a click wheel on the back of the hand and (e) a headset control behind the ear.

ABSTRACT
We propose *iSkin*, a novel class of skin-worn sensors for touch input on the body. iSkin is a very thin sensor overlay, made of biocompatible materials, and is flexible and stretchable. It can be produced in different shapes and sizes to suit various locations of the body such as the finger, forearm, or ear. Integrating capacitive and resistive touch sensing, the sensor is capable of detecting touch input with two levels of pressure, even when stretched by 30% or when bent with a radius of 0.5 cm. Furthermore, iSkin supports single or multiple touch areas of custom shape and arrangement, as well as more complex widgets, such as sliders and click wheels. Recognizing the social importance of skin, we show visual design patterns to customize functional touch sensors and allow for a visually aesthetic appearance. Taken together, these contributions enable new types of on-body devices. This includes finger-worn devices, extensions to conventional wearable devices, and touch input stickers, all fostering direct, quick, and discreet input for mobile computing.

Author Keywords
On-body input; Mobile computing; Wearable computing; Touch input; Stretchable, flexible sensor; Electronic skin.

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H.5.2. Information interfaces and presentation: User Interfaces – Input devices and strategies

INTRODUCTION
The human skin is recognized as a promising input surface for interactions with mobile and wearable devices. However, it has been difficult to design and implement touch sensors that can be placed directly on the skin. We present iSkin, an input surface for mobile human-computer interaction on the human body. iSkin is a thin, soft, flexible, stretchable and visually customizable overlay that is worn directly on the skin. It is custom-shaped and can be attached at many different locations on the body. The interactive surface is "always available" and allows for quick and discreet interactions — either standalone or as an input surface for other mobile devices. Its unique properties open up new possibilities for mobile interaction that have not been possible with existing hardware. Figure 1 shows example applications of our current implementation. One example is a very thin, yet large input area, which can be wrapped around a finger and is stretchable enough to be worn over joints. It features three touch buttons of the size of a fingertip and one linear slider with five elements. It allows for fast and direct control of mobile devices using touch input even when the hands are busy.

iSkin relates to the emerging stream of on-body interaction, e.g. [1, 6, 8, 9, 10, 16, 24, 35, 36]. It is technically based on advances in electronic skin (e-skin) and soft-matter electronics [7, 18, 30, 33], an active research field in robotics and material science. To our knowledge, our work is the first investigation into how electronic skin can be used for on-body interactions to control mobile computing devices; this includes interactive scenarios, sensing techniques, form factors and device types as well as aesthetics. We present the following main contributions:

1) The implementation of touch-sensitive iSkin, a biocompatible, stretchable soft-matter sensor. It combines capacitive and resistive sensing with a new electrode design to sense touch input with two levels of pressure. An electrode size of 8 mm led to a high signal-to-noise ratio. Study results show that the sensor remains functional under typical and extreme deformations that occur on the human body and accurately senses touch input when worn on various body locations.

2) We address visual aesthetics of the sensor, considering the important role of aesthetics for any body-worn accessory (e.g., [19, 37]). Our sensing approach is visually customizable to support aesthetic designs; the conductive traces and electrodes act as (part of) the visual artwork. This paper contributes general design patterns for sensor designers to convert graphical designs into a functional touch sensor.

3) We implement novel types of skin-worn devices, in order to explore usage and interaction scenarios of iSkin (Figure 1). These devices highlight different locations and contexts of use, different form factors, and different interactions.

The remainder of the paper starts with a review of related work, before we introduce design goals for skin-worn touch sensors. Next we present the implementation of the sensor and discuss how to realize visually aesthetic sensors. We show application examples and results from two evaluation studies. We conclude with a critical discussion on outstanding challenges for skin-worn touch sensors.

RELATED WORK

Our research is informed by prior work in the areas of electronic skin and on-skin input:

Electronic Skin

iSkin is based on recent advances in electronic skin (e-skin). E-skin makes the "effort to create an artificial skin with human-like sensory capabilities" [7]. Research in this area started with the seminal work of Lumelsky et al. [18] and Someya et al. [33]. Primary fields of study include multimodal sensor skins that allow robots to better sense their direct environment; soft prostheses that are capable of sensing contact, pressure or temperature; and health-monitoring devices [41].

Advances in e-skin [7, 32, 30] and materials science now allow for exploration of a novel application domain: on-body interaction for mobile computing. iSkin is the first investigation into this domain for the field of HCI, introducing e-skin into the recent stream of on-body interactions. Compared with temporary tattoos [14] or in the future possibly even implants [12], a skin overlay is easily attachable and detachable, which in our opinion is an important factor for its success as a consumer product.

In the materials science community, first proofs of concept have shown the technical feasibility of sensor overlays for touch sensing on the body [15, 17, 42]. Kramer et al. presented a pressure sensitive skin overlay composed of PDMS embedded with microfluidic channels of eutectic gallium-indium (EGaIn) alloy [15]. Lu et al. [17] have demonstrated the feasibility of patterning cPDMS with a laser engraver to produce an alternative to EGaIn for soft-matter sensors and circuits. This allows for tactile sensing through direct electrical contact between the circuit and human skin. However, sensing with exposed electrodes is not very reliable because skin conductance heavily varies between users and electrodes might become stained or worn through skin contact, increasing resistivity over time. Woo et al. demonstrated pressure and strain measurements using a compressible layer of EcoFlex [42]. While the measurement is continuous, the sensor is unable to differentiate between pressure and strain. Furthermore, this approach relies on microcontact printing and cleanroom microfabrication and therefore lacks possibilities for rapid customization. Our sensor adds to this body of research by capturing two levels of normal force independently of how much it is stretched, an important requirement for robust on-body input. Moreover, it is compatible with rapid prototyping in a simple lab environment and can be visually customized for an aesthetic appearance.

On-Skin Input

The HCI community has presented several sensing techniques to capture input on the skin for interaction with mobile devices. Prior work can be split into four sensing approaches. One is camera-based sensing, with RGB cameras [20, 36] or depth cameras [3, 8, 9, 21]. This allows for interacting directly on the skin, but requires direct line-of-sight to a camera and is susceptible to lighting conditions. Second, bio-acoustic sensors [10] work on many body locations and do not require a sensor overlay, at the cost of low spatial sensing resolution and single-touch-only sensing. A third approach consists of magnetic sensing [1] using magnets and Hall-effect sensor grids attached to the body. Those approaches do not require a skin overlay, but fall short in detecting precise touch-down and touch-up events. We designed iSkin to be thin and soft enough to retain much of the sensory stimulation that occurs naturally and upon touch. Finally, photo-reflective sensing [23] is based on two armbands with infrared reflective sensors. These are able to recognize deformations of skin, but do not recognize touch, which has been suggested to be the most important on-skin modality [40].

iSkin also relates to flexible sensors for smart clothing and wearables [13, 16, 27]; those support interaction in close proximity to, but not on, skin. In addition, iSkin is related to flexible touch sensors for use on objects [4, 28, 29]. These are well suited for rapid prototyping of input on non-planar surfaces. However, these approaches were not intended to be used on skin and thus are not elastic, biocompatible and robust enough for skin interaction. Finally, prior work has recognized the importance of aesthetics for body-worn interfaces [37]; we address this requirement with a visually customizable sensor.

DESIGN GOALS FOR iSKIN

This section outlines important requirements and opportunities for the design of skin-worn touch sensor overlays for mobile computing. While prior work on electronic skin has focused on addressing questions related to skin-compatibility of materials, sensing modalities and data processing, we introduce several new dimensions that are of critical importance when the sensor overlay is used as a human-computer interface. This includes locations of use, form factors of devices, visual appearance as well as input and output for control of computing devices. These goals guide our design and implementation of iSkin.

1. Skin Compatibility: The human skin is a living organ. Poorly designed sensor patches could adversely affect its physiological functions, including protection, thermal regulation, sweating, bacterial ecosystem, oxygen intake, and sensation. iSkin should be non-toxic, and easily cleanable, washable, or replaceable in order to limit the accumulation of pathogens such as bacteria. Moreover, the properties of skin vary greatly. These include thickness, stretchability (around 20%[30]), wrinkliness, oiliness, and the distribution of receptors, sweat glands, and hair follicles, which vary both across body locations and across individuals. This requires materials and adhesives that are compatible with natural skin and exhibit a high variability of form factors. iSkin should be as thin as possible to fit closely to the skin and to support localizable tactile feedback upon pressing the sensor. Moreover, iSkin needs to be lightweight, soft, flexible and stretchable to be worn comfortably during movement, stay in place and resist external stress.

2. Locations: iSkin should support placement on arbitrary locations on the body. Informed by previous work, we distinguish three primary locations:

1) Hand. If placed on the palm, sensors need to be thin and flexible to bear strong deformations. The back of the hand is less deformable. Both dorsal and palmar aspects of the hand are promising for interaction with a smartwatch [21], remote devices [3] or imaginary devices [6]. Fingers are another promising location. Prior work has started to explore wearable finger input with, for example, fingernail displays [34] and fingertip interaction [1]. However, these solutions augment only a specific part of a finger, are rigid, and are still quite thick. In contrast, iSkin can be applied over the entire finger, including the joints.

2) Arm. The forearm and upper arm provide a large surface that is often uncovered. While the forearm is easy to access, deemed socially acceptable [38] and a preferred location to touch [40], the upper arm is less preferred for touching [40].

3) Head. iSkin can be attached to the face, for instance on the cheek for capturing touch inputs with a head-mounted-display [31] or digital jewelry. It also can be worn on less visible areas, such as behind the ear (see also [16, 36]).

We demonstrate that iSkin can be worn on these locations. In addition, its flexibility allows for exploration of other on-body locations as well as use underneath or on top of clothing.

3. Device Types and Form Factors: iSkin should be easy to attach and detach, regardless of the location on the body, yet robust to movement and wear. It allows for multiple novel device types: First, it can be wrapped around a body part, similarly to a bracelet or ring (Figure 1a). Unlike rigid electronics, iSkin can be placed close to or on joints due to its stretchability. Second, iSkin can be affixed to body-worn devices (e.g. a smart-watch, Figure 1b), accessories or smart clothes (e.g. [13]). In these cases, the flexibility and stretchability of iSkin allows for rolling and folding, enlarging it on demand for larger input surfaces. Finally, iSkin can be attached directly on the skin (e.g. Figure 1c–e), similar to a patch. Skin-friendly adhesives used for cosmetics and the medical domain can be used to allow for an easy attachment. The size of devices needs to be scalable and their shape adaptable to be worn on many different locations of the body and to suit the highly varying anthropometric distributions of people with different geometries. The thin-film material of iSkin could even support ad-hoc customization through cutting, as proposed in [26].

4. Visual Customization: Visual appearance is an important requirement for social acceptability. The appearance of skin is observed by others, signaling traits related to personality, health, and social status. Many cultures have developed sophisticated traditions of decorating the skin. iSkin should thus be inconspicuous, for instance by making most parts transparent, but also customizable and aesthetically pleasing. The possibilities for aesthetic design include visual ornaments and designs inspired by the existing cultures of body art, such as tattoos and jewelry.

5. Input: iSkin should provide sufficient control to let users quickly and accurately perform input commands on the sensor surface. The sensor should also avoid accidental activation. The input possibilities include, at minimum, touch, multi-touch, pressure, and proximity sensing. Our iSkin implementation is presently able to detect two-level touch input with precise touch-down and touch-up events. Moreover, the wiring principles enable flexible layouts of input regions. This allows for multiple interaction elements, such as sliders, rotation wheels and other useful widgets.

6. Output: iSkin itself is an input interface. It allows for static visual guidance by indicating interactive areas. However, due to the flexible placement of the sensor, and especially if coupled with wireless communication, it can be combined with many additional output devices: smartphones, smartwatches, laptops, or nearby computers.

7. Interfacing and Processing: The sensor is connected with a controlling unit, which processes sensor data, supplies energy, and communicates with a nearby computer device. Advances in thin-film electronics suggest that in the future these are very likely realizable in flex and can be embedded within the flexible sensor. Presently such components need to be realized as rigid, conventional components. Scaled down, the rigid components could be attached right onto the sensor surface. While interfacing and processing is not the focus of our paper, we show that a fully functional and mobile system can be realized today.

Taking these design goals into account, realizing a touch-sensitive skin overlay is a challenging endeavor. While flexibility alone poses demands that go well beyond conventional rigid electronics, stretchability adds further significant challenges. This calls for using different base materials and new elastic conductors, novel electrode designs for soft-matter electronics and adaptation of sensing techniques. In the next section, we present the implementation of touch-sensitive iSkin that fulfills the key goals outlined in this section.

iSKIN SENSOR

This section describes manufacturing steps and our sensing implementation of touch-sensitive iSkin. We first introduce PDMS and cPDMS as promising soft matter materials for elastic user interfaces in HCI and describe how to produce and process these materials in a simple lab environment. Knowing about these materials might be helpful for the HCI community for realizing all sorts of elastic user interfaces beyond our concrete sensor implementation. Then we contribute a sensor design for capacitive and resistive sensing of on-skin touch input. Our approach is capable of distinguishing between two levels of pressure, allows for sensing of precise touch down and up events, supports flexibly shaped and freely arranged interactive areas, and last but not least, is very robust to stretching and bending.

Materials

iSkin is made of multiple layers of thin, flexible and stretchable silicone. The base material is polydimethylsiloxane (PDMS), an easy-to-process silicone-based organic polymer. PDMS is fully transparent, elastic, and a highly biocompatible material. Therefore it is widely used on or in the human body, for example in body implants. It has also been used for soft matter electronics in HCI. It is not conductive.

An elastic conductor can be realized by filling PDMS with carbon black particles, yielding cPDMS (carbon-filled PDMS). The carbon particles make the material appear black and opaque. PDMS and cPDMS are permeable to oxygen, but cPDMS does not oxidize at room temperature. Therefore the electrical resistance of the electrodes remains fairly stable over time.

Compared with other elastic conductors, such as liquid phase conductors [15], conductive meshes [11], or AgPDMS [17], cPDMS is very cheap, can be realized in a thinner form factor and neither encapsulates nor exposes harmful substances.

The cost of material for a letter-sized sheet is about $1. Therefore the sensor patch can be designed for one-time use, if desired. Alternatively, it can be used for a longer time without problems, as the material is robust, can be cleaned with water and can even be disinfected for hygienic reuse.

Fabrication

iSkin is easy to fabricate, both for prototyping purposes and in industrial production. PDMS is produced by mixing a silicone elastomer base with a silicone elastomer-curing agent (both from Sylgard 184; Dow Corning, Inc.) in a weight ratio of 10:1. For cPDMS, 13% (by weight) of acetylene carbon black powder (Alfa Aesar) is added to the uncured mixture of PDMS (weight ratio 20:1). The material can be formed to thin films using a spin-coater or thin-film applicator. We found that it helps to make the cPDMS film very thin ($\approx 100\,\mu$m), as this reduces sedimentation of the carbon black powder to the bottom of the film during curing, which would result in a lower conductivity.

The functional sensor is produced with laser-patterning using a method introduced in [17]. Figure 2 shows the composite structure of our sensor, which is composed of PDMS and cPDMS layers. Before application, the layers are laser-patterned to create conductive lines and electrodes (in cPDMS) or insulating areas (in PDMS). We use a 30W laser engraver from Universal Laser Systems (VLS 3.50) for patterning. Each layer is bonded to the composite by adding a very thin layer of uncured PDMS as connective glue. As soon as the PDMS is cured, the layers are firmly attached. To increase breathability, the final sensor could be perforated as described in [39].

On-Body Touch Sensing

Sensing touch input on the body with cPDMS faces multiple challenges. First and foremost, cPDMS is a very poor conductor. Its resistance is as high as $100\,\Omega\,$m [22] and further decreases when it is being stretched (it even takes several hours to go back to its initial resistance). Secondly, both capacitive and resistive sensing exhibit unique challenges: permanent contact with human skin results in added capacitive coupling, while the curvature of the body disallows using the standard approach for inter-layer spacing in resistive touch sensing. In the following, we address these challenges and show how to implement robust touch sensing. We present a soft-matter electrode design that supports both projected capacitance and resistive touch sensing. Both techniques give precise real-time information about touch down and up events. Both modes combined allow for distinguishing between two levels of touch pressure. In contrast, resistive sensing alone is less prone to accidental input, as more pressure is required to trigger a touch down event.

Electrode Design

Both sensing techniques share the same physical structure, illustrated in Figure 2a: two embedded electrodes are overlaid and held apart with a spacing layer. The embedded conductive traces and electrodes are realized with cPDMS. We use solid layers of PDMS on top and on the bottom to seal off the electrodes from contact with skin and the environment. PDMS is also used for the spacing layer in between both electrodes. The spacing layer is solid at areas where no electrodes are located; it is permeable in between electrodes, to allow for pressure creating a conductive connection. At areas where no electrodes or wires are laid out, only the transparent base layer needs to be realized. The sensor is very thin: from $190\,\mu$m at areas where no electrodes or wires are laid out to approx. $700\,\mu$m at locations where all layers are realized. Given the high resistance of cPDMS, conductive traces need to be fairly wide. We identified the minimal width of a trace for robust conductive connection to be 1 mm.

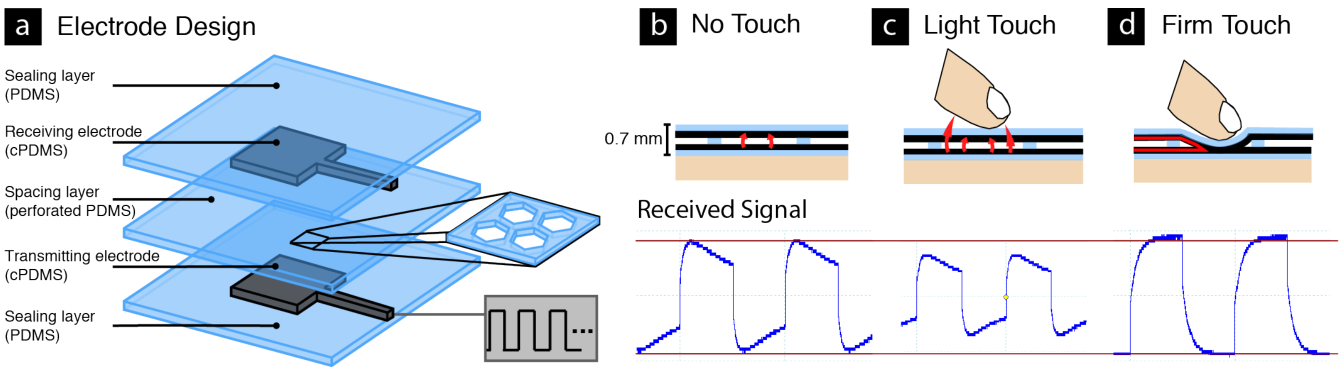

Figure 2. iSkin Touch Sensing: (a) Overview of layers in a touch-sensitive iSkin; (b) sensing without touch contact; (c) projected capacitive sensing of slight touch events; (d) resistive sensing of firm touch events.

Capacitive Sensing for Light Touch Contact

Projected capacitive sensing uses capacitive coupling between the two electrodes (Figure 2b). The bottom electrode connects to a 5 V square wave signal of 1.000 kHz generated by a wave generator (Agilent 33210A). If the sensor contains several separate touch-sensitive areas, the top electrodes are time-division multiplexed to sequentially measure the transmitted signal on each of them. The received signals are processed by a PC oscilloscope (PicoScope 6402A). Bringing a finger near the surface of the sensor changes the local electric field, which reduces the mutual capacitance. Therefore the signal amplitude decreases (Figure 2c). After calibration, the sensor can reliably detect touch events despite the high resistance of the conductor. The sensor needs to be calibrated after it is applied to the skin. It reacts on very slight touch contact, as known from commercial capacitive touch sensors.

Resistive Sensing for Firm Pressure

Resistive touch sensing relies on pressure to create a contact through the permeable spacing layer between both electrodes. A firm touch physically closes the circuit (Figure 2d). In this case, the waveform of the received signal on the upper electrode is changing, serving as a reliable indicator for firm touch.

To ensure both layers are reliably spaced apart even when they are curved or stretched, our solution uses uniform tiling with a hexagon pattern, similar to honeycombs. This improves the robustness against deformations occurring on the body while minimizing the required spacing material to decrease the required pressure for touch detection. For our prototypes we used a hexagon diameter of 1.5 mm.

Sensing of Two Levels of Touch Pressure

Combined projected capacitive and resistive sensing enables sensing of two levels of normal force: capacitive sensing detects light touches, while resistive sensing detects firm touches. The sensing techniques use the same physical electrode structure, the same sensing circuit and are performed in the same sensing cycle. Therefore, the frame rate of sensing is not reduced. Figure 2b–d shows an example of the values captured for light and firm touches.

Results from our technical evaluation below show that this approach is capable of reliably distinguishing between both pressure levels, independently of how much the sensor is stretched or bent. We consider this robust detection to be a very important requirement for successful on-body interfaces. While continuous normal force could in principle be captured using a force-sensitive resistor approach, sensor readings would be corrupted by large changes in resistance that result from stretching, which naturally occurs during use on human skin.

Interactive Widgets

The electrode design of both techniques allows for flexibly shaped interactive areas and senses precise touch down and touch up events. This allows for designing more complex widgets, such as sliders or click wheels. An example of a five-element slider is implemented in the FingerStrap (Figure 1a) and the EarSticker (Figure 1e), the click wheel as a WheelSticker (Figure 1d).

Interfacing and Data Processing

The flexible sensor patch is tethered with a ribbon cable to an Arduino-compatible microcontroller (Teensy 3.1), which is processing the data and driving the sensor. Signal measurements are time-division multiplexed with a frequency of 17 kHz. For interfacing, the sensor has a connector area, on which all pins are exposed. A custom-made rigid connector board is attached to these pins using z-axis conductive tape. Its other side is connected to wires leading to the microcontroller. An additional transparent adhesive tape on the top of the connector further stabilizes it and avoids lateral shifting of the connector board on the sensor. The connector area can be laid out anywhere on the sensor patch where no interactive area is located.

DESIGN PATTERNS FOR VISUALLY CUSTOMIZABLE SENSORS

Aesthetic visual appearance is a prime requirement for social acceptance of body-worn devices. Inspired by an example of an aesthetic sensor [5], we contribute guidelines for the development of sensors which integrate aesthetics and electronic functionality. These patterns help designers transfer an existing vector graphic into a functional sensor design. Electrodes and circuitry are laid out in a visually appealing way, following the vector graphic, while retaining their electronic functionality. Hence, the function of black cPDMS becomes two-fold: (1) providing electronic functionality, by serving as wires and electrodes for touch sensing, and (2) providing a visually appealing graphical design.

While we demonstrate these principles with cPDMS, they transfer to other conductors, such as AgPDMS, CNT-PDMS and printable inks.

Our design patterns work particularly well for connected line art, filled shapes, and silhouettes. In a first step, the designer chooses a black-and-white vector graphic to transfer into a sensor. Afterwards the graphic can be transferred into a functional sensor using a vector graphics application and the following patterns.

Fully Touch-Sensitive Graphic

To make all elements of the graphic (i.e. all black areas) touch-sensitive, the designer proceeds as follows: one pair of overlaid electrodes is created, each having the exact shape of the black part of the graphic (Figure 3a). Both electrodes are separately tethered to a connector area. To support resistive sensing, the spacing layer is perforated between the upper and lower electrodes. Hence, the entire graphic acts as one touch area. Note that the white parts of the original graphic appear transparent on the sensor and are insensitive to touch.

Correct electronic functionality puts some additional demands on the graphical design: the electrode must be one connected shape and all traces must be wide enough for a robust conductive connection. Hence, if the graphic contains disconnected components, these need to be connected with a trace. If a trace is too narrow, the designer can either scale up the entire graphic or dilate the narrow parts of the graphic. These visual changes are often subtle enough not to affect the overall appearance.

Partially Touch-Sensitive Graphic

If only some part of the graphic should be made touch-sensitive, the sensitive part can be implemented following the pattern above. Non-sensitive areas are realized with a solid spacing layer, in order to prevent resistive contact. To prevent capacitive sensing between the transmitting and the receiving electrode at non-sensitive areas, the design is slightly modified: instead of overlaying two electrodes with exactly the same shape, the visual design is realized by two non-overlapping electrodes. The top electrode realizes one half of the visual graphic, while the bottom electrode realizes the other one (Figure 3b). Due to the close proximity of the top and bottom layers, both parts appear as a uniform solid shape to the human eye.

Graphic with Multiple Sensitive Areas

Multiple touch-sensitive areas within one graphic can each be directly connected with the connector through separate traces (Figure 3c left). Some interactive areas are only addressable by having their trace go through another interactive area (Figure 3c right). In these cases the connection can be routed along the border of the area. This reduces the size of the interactive area, but leaves the visual appearance of the graphic unmodified.

Support of Fine Detail

Parts of the graphic that contain fine details, e.g. thin letters, ornaments or contours, cannot be made touch-sensitive if the visual elements are finer than the minimum width of conductive traces. While the details can still be realized and remain visible, they cannot act as a conductor for a robust connection and therefore remain insensitive.

One solution to support fine detail is to invert the graphic (Figure 3d top). The graphical elements are laid out in white while the surrounding area becomes black. Instead of the (fine) details, the (larger and wider) surrounding area is now sensitive to touch.

Another option is to add a layer of color on top of a black touch-sensitive area. This layer can add details and provide visual guidance without modifying the design of the interactive area. This allows, for example, adding labels for keys on the keyboard in Figure 3d bottom.

Non-Sensitive Visual Elements

It is possible to add insensitive visual elements, e.g., for aesthetic decoration (Figure 3e), for additional labels, or to create a coherent visual appearance. Such non-sensitive visual elements are added to the bottom electrode layer. As long as they are disconnected from other elements on the bottom layer and are not overlaid with elements on the top layer, they do not interfere with sensing.

Adjusting the Physical Shape of the Sensor

Lastly, a designer can freely choose the shape of the sensor by cutting the surrounding PDMS into the desired shape (Figure 3f). This allows for a better fit on various body parts but can also enhance the visual appearance of the sensor.

Summary

The above-mentioned patterns help designers to manually transfer a graphical design into a functional sensor. Figure 1 shows examples of sensors based on these patterns. Our presented iSkin designs use only black traces on a transparent base substrate. Future sensors could be colored by adding colored traces or areas to the (non-conductive) PDMS top layer of the sensor. A design environment for iSkin sensors can be created using the presented patterns. This environment could provide guidance to the designer, e.g., warning if traces are too narrow, or even (partially) automate the conversion of the vector graphic into a functional sensor.

APPLICATION EXAMPLES

iSkin enables several classes of interaction and supports various scenarios. We present prototypes of three novel on-body device classes. They support a wide variety of body locations demanding different sizes and shapes, different sensor designs and various degrees of flexibility and stretchability. They are organized in three groups, highlighting the flexibility in attachment of the sensor on the human skin: wrapping around body parts, attaching to on-body devices, and sticking onto the skin using biocompatible adhesives.

FingerStrap

The FingerStrap (Figure 1a) is a touch-sensitive film wrapped around the middle segment of the index finger to support microinteractions. Compared to ring-like devices, the strap

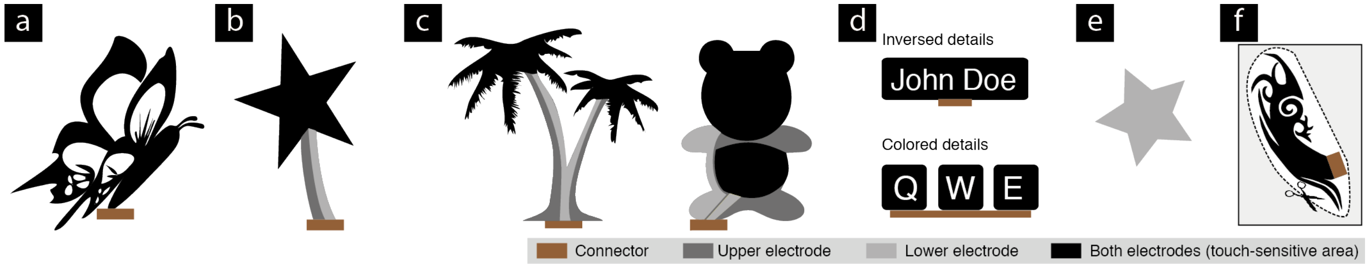

Figure 3. Design Patterns for Visual Customizations: (a) fully touch-sensitive graphic, (b) partially sensitive graphic, (c) graphic with multiple interactive areas, (d) touch-sensitive detail using inverse and color patterns, (e) non-sensitive visual elements, and (f) shape customization.

increases the input space by covering a larger area without preventing movements. It features three buttons and a touch slider with five sensitive areas, all integrated in a tattoo-like visual design. It uses resistive sensing to avoid accidental activation by requiring a certain limit of pressure. FingerStrap is especially useful when the hands are busy with a primary task (e.g. driving a car). It supports eyes-free input. Simple finger movements such as a slide of the thumb on the index finger can activate a command. It can also be used for casual interactions such as discreetly rejecting a call during a meeting or controlling a stopwatch during sports activities.

Extension for Wearable Objects

This prototype of a rollout keyboard can be attached to a smartwatch (Figure 1b). It enlarges the input space by letting the user interact on skin in the vicinity of the watch. The keyboard can be fully rolled in to be portable and can be pulled out on demand to overlay the skin of the forearm, as shown in Figure 1b. It provides a large input area for entering text using a full QWERTY keyboard with 30 keys. This highlights the possibility of sensing many interactive areas using a grid-like structure and time-division multiplexing.

SkinStickers

This class of interaction devices is useful for fast and direct selection of one or several frequent operations. While a SkinSticker can be attached virtually anywhere on the body, the forearm is suggested as a convenient location for quick and direct access [40, 38]. To attach the sensor patch onto skin, we use mastic. This is a medical-grade adhesive for use on skin. It is inexpensive (less than 0.40 USD/ml), can be easily applied, and is fully compatible with use on skin. After use, the sensor can be easily peeled off without hurting the skin and without tearing out body hair. Previous work reported successful use of ADM Tronics Pros-Aide medical grade adhesive [12]. We show three SkinStickers for different functionalities:

MusicSticker. MusicSticker supports several functionalities in a visually aesthetic design, as shown in Figure 1c. It contains five interactive areas for controlling a music player: Play, Previous, Next, Vol+ and Vol-.

ClickWheel. We have implemented a ClickWheel sticker (Figure 1d). It captures circular rotation gestures. Moreover, touching and pressing on a segment differentiates between two commands.

EarSticker. Inspired by Earput [16], EarSticker (Figure 1e) can fully exploit the flexibility, stretchability and the affordances for input on the back of the ear and the earlobe. It supports input related to audio, such as adjusting the volume.

EVALUATION

Stretchability and Bendability

We evaluated stretchability and bendability of the sensor in a controlled setup. It includes typical and extreme sensor deformations, which occur on the human body.

Methodology. We used a rectangular sensor (8.5 cm/4 cm) with an electrode diameter of 1.5 cm, conductive trace width of 1 mm and a thickness of 700 µm. This reflects the properties of the sensors in our application scenarios. The sensor was stretched by 0%, 10%, 20% and 30%. Moreover, it was bent around 3D printed cylinders of four radii: 0.5 cm, 1 cm, 2 cm, and 3 cm. These situations cover typical and extreme deformations when worn on the body. In each condition, 10 consecutive touch contacts were created using a circular shape of fingertip-sized diameter (8 mm) in resistive sensing and with a human fingertip for capacitive sensing. For each experiment we used a different sensor to avoid one experiment influencing the other. All measurements were taken with increasing stretch and curvatures.

Results. Figure 4 depicts the results for each condition. This includes changes in resistance of the circuit, the average peak-to-peak voltage readings for capacitive sensing of slight touch contact as well as the average normal pressure required for

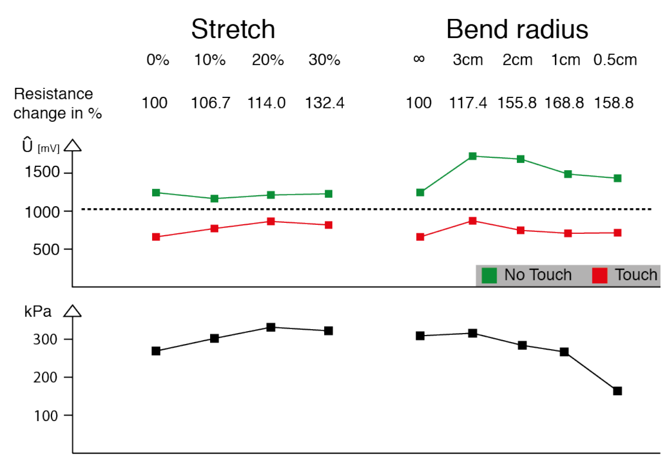

Figure 4. Results of the technical evaluation: (a) relative change in resistance, (b) measured voltage $\hat{U}$ for capacitive touch contact and no touch, (c) required pressure for resistive touch contact.

Figure 5. Study setup on the participants' forearm, back of the hand and finger. Two straps of Velcro allowed for fast and easy attachment.

creating a contact using resistive sensing. First and foremost, the data shows that in all test conditions the sensor remains functional and sensitive to touch on both pressure levels. Secondly, as indicated by the dotted line in the capacitive sensing chart, touch vs. no touch can be classified without knowledge of how much the sensor is currently stretched or bent. Thirdly, the pressure required for resistive sensing of touch remains fairly stable. A smaller bend radius decreases the required force since bending reduces the distance between the electrodes. While resistive sensing requires a firm touch, it can be a useful mode to support in addition to capacitive sensing, which reacts to very light touches. The required pressure can be tuned by changing the diameter of the hexagon pattern.

Reliability Across Body Locations

In a user study we investigate the accuracy and robustness of the touch sensor when worn on various body locations.

Methodology. Twelve voluntary participants (4f, mean age 26.8y) were recruited for the study. We used a rectangular sensor with one circular electrode having a diameter of 1.5cm, which is a recommended size for capacitive sensing elements [2]. It was attached directly on the users skin using two straps of Velcro (see Figure 5). The upper limb rested on a table to avoid fatigue effects influencing the results. Participants were seated and asked to keep arm, hand and fingers steady. We evaluated touch contact (capacitive sensing) and firm pressure touch (resistive sensing) on three body locations, reflecting the main locations identified in the design goals section: the forearm, the back of the hand, and the index finger. The order of body locations was randomized. In each condition, the task consisted of repeatedly touching the sensitive area in 1.5 s intervals, as accurately as possible. The participant was guided by an auditory metronome and received additional auditory feedback when the sensor was detecting touch contact. Participants were allowed to practice until they felt comfortable with the task. Touch events were logged on a computer with a PC oscilloscope (PicoScope 6402A). We collected a total of 4,320 touch inputs (360 per participant). Each session took approximately 15 min. The reported accuracy is the percentage of correctly recognized touch contacts (exactly one touch event recorded for one touch contact).

Results. The average accuracy was 92.5% (SD=11.2) for touch contact and 98.1% (SD=2.8) for firm pressure touch. For touch contact, it was highest on the forearm (93.0%), followed by the finger (91.2%) and the back of the hand (91.1%). For firm pressure touch, accuracy was also highest on the finger (99.2%), followed by the back of the hand (98.5%) and the forearm (97.6%). It is noteworthy that the task was more challenging than typical real-life scenarios due to the timing requirement, giving us a conservative estimate of accuracy. The lower accuracy of capacitive sensing compared to resistive sensing can be explained by the simple classification method we have used, which was merely based on measuring raw peak-to-peak voltage and did not make use of any signal conditioning. It seems quite safe to assume that a dedicated processing unit for capacitive touch sensing will lead to higher accuracies. We conclude that these results provide a lower bound, showing acceptable (91.1%) to very good (99.2%) results despite the proof-of-concept level processing of sensor data. This provides first evidence for suitability of the sensor for practical on-body input tasks.

LIMITATIONS AND FUTURE WORK

While it has been shown that the present design suffices for novel application-specific designs for touch input on the skin, four important challenges remain for future work: 1) extending input capabilities and modalities, 2) reduction of unintentional input, 3) system integration for mobile computers, and 4) investigating comfort and human factors.

First, the *size of interactive areas* of the demonstrated prototypes are comparable to a fingertip, the smallest one has a diameter of 8 mm. This size yielded a high signal-to-noise ratio (SNR) of 44.4 for capacitive (robust capacitive sensing requires $\approx$ 15 [2]) and 16.8 for resistive sensing. These results indicate potential for further decreasing the size of electrodes while maintaining robust sensing, but future work is necessary to provide a reliable lower bound. The prototypes also have rather low *spatial resolution* of touch sensing. This can be increased by creating denser grid-like sensing areas (e.g. used in the keyboard sensor). The smallest spacing between buttons we have tested was 1 mm. Capacitive crosstalk between electrodes turned out not to be a problem. Despite the neighboring electrode being touched, the SNR only decreased by 15.1%. This still allows for robust sensing using a naïve threshold. Future work could interpolate between the electrodes to improve resolution. Both size and resolution are limited due to the high resistance and inhomogeneity of cPDMS, which requires conductive traces to be fairly wide (we experienced 1 mm to be a good wire width). One solution would be to use AgPDMS instead of cPDMS. This would make the sensor more expensive, but the principles introduced in this paper transfer to AgPDMS. The number of available pins on the controller board could be easily increased by using multiplexers. Our sensor can simultaneously sense multiple touch contacts, making it suitable for use with multi-touch interfaces once the resolution increased.

Continuous pressure is another dimension to consider. The high and inhomogeneous resistance of cPDMS makes it very challenging, if not impossible, to use the FSR principle for reliable measurement of continuous pressure. Furthermore, stretching and deforming the material increases resistance by up to a factor of two, and it remains elevated even if the material has retracted to its original shape, regaining the original resistance only after several hours.

We envision future iSkin to sense *more modalities than touch*. iSkin could sense body movements by embedding MEMs, or access biofeedback for health-related applications [39, 41], e.g. body temperature. In addition, environmental sensing, such as air quality or UV radiation, could be included. Future iSkin could also provide visual output through an embedded thin-film display. While it has been shown that customized and deformable thin-film displays can be easily fabricated [25], it is still unclear how to produce stretchable displays.

Second, we have focused on detection performance for touch events rather than avoiding unintentional input. Future work should investigate when and how in daily use the iSkin sensor is in contact with other body parts or objects. This will allow for fine-tuning the sensor's sensitivity by tuning sensing parameters and the density of patterning of the spacer layer. Besides physical contact, also body movements can influence capacitive sensing. In our experience, typical movements do not reduce the accuracy of sensing, while a few extreme movements (e.g. a strong arm swing) require better processing, e.g. usage of a commercial capacitive touch sensors. In general, temporal and spatial input patterns can help identify and remove unintended contacts.

Third, integrating iSkin to a mobile computer is a challenge for future work. Although iSkin is a stretchable and thin touch sensor, the connector and micro-controller are still rigid. These parts could be made wireless using ad-hoc networks for communication with other body-worn devices. The electronics themselves could be either incorporated in the flexible and stretchable sensor surface or be miniaturized and attached as a small rigid pin. This would allow on-device computation and display for feedback. Instead of relying on external devices, the design of iSkin patches might also incorporate some visual display, for example by exploiting advances in thin-film displays. Moreover, audio output could be realized with integrated printed speakers. Haptic output is a further very promising channel as iSkin is directly located on the skin. For instance, temperature feedback can be quite easily realized by printing a resistor made of cPDMS.

Finally, although our results are promising in terms of comfort and safety, we see many ways to improve. In particular, future work needs to consider a more thorough exploration of the impact of skin overlays on tactile feedback. While direct-on-skin sensing can provide better sensory stimulation, skin overlays have the advantage of precisely delimiting the interaction area and providing static visual information on the interactive functionality.

SUMMARY AND CONCLUSION

This paper has contributed the design of a novel class of skin-worn touch sensors. The underlying technical solution of iSkin builds on and extends recent advances in research on electronic skin. iSkin is a proof of concept of on-skin touch sensing that bears some promise over rigid sensors and computer vision based solutions. iSkin supports touch input on the skin. While depressing the skin for input does not offer the dynamic properties of physical buttons, it does retain some of the known benefits for tactile feedback and supports eyes-free input on the body through proprioception.

The technical solution allowing this is based on embedded carbon-doped electrodes and combined capacitive and resistive sensing. A technical evaluation showed that this solution supports bending around radii of 5 mm and stretching by 30% and is therefore well suited for on-body interaction.

The design of iSkin supports the customization of touch sensors to specific applications and body locations, desired visual appearance and button layouts. This has allowed us to create applications to very challenging body parts, like the index finger or the back of the ear. Moreover, while we are far from a generic controller for mobile devices, we can already cover some essential aspects like unidimensional selection tasks and text entry.

We hope that this paper will stimulate future research on electronic skin for mobile human-computer interaction, leading to multimodal input-and-output skins that improve interaction with mobile devices in a wide variety of tasks and activities.

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