Interactive On-Skin Devices for Expressive Touch-based Interactions

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by
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Abstract

Skin has been proposed as a large, always-available, and easy to access input surface for mobile computing. However, it is fundamentally different than prior rigid devices: skin is elastic, highly curved, and provides tactile sensation. This thesis advances the understanding of *skin as an input surface* and contributes *novel skin-worn devices* and their *interaction techniques*.

We present the findings from an elicitation study on how and where people interact on their skin. The findings show that participants use various body locations for on-skin interaction. Moreover, they show that skin allows for expressive interaction using multi-touch input and skin-specific modalities.

We contribute three skin-worn device classes and their interaction techniques to enable expressive on-skin interactions: *iSkin* investigates multi-touch and pressure input on various body locations. *SkinMarks* supports touch, squeeze, and bend sensing with co-located visual output. The devices' conformality to skin enables interaction on highly challenging body locations. Finally, *ExpressSkin* investigates expressive interaction techniques using fluid combinations of high-resolution pressure, shear, and squeeze input.

Taken together, this thesis contributes towards expressive on-skin interaction with multi-touch and skin-specific input modalities on various body locations.

Zusammenfassung

Die Haut wurde als große, immer verfügbare und leicht zu erreichende Eingabefläche für Mobilgeräte vorgeschlagen. Es gibt jedoch fundamentale Unterschiede zwischen der Haut und starren Mobilgeräten: Haut ist elastisch, uneben und berührungsempfindlich. Diese Arbeit untersucht die *Interaktion auf der Haut* und ermöglicht diese mit *neuen Eingabegeräten*.

Wir präsentieren die Ergebnisse einer Nutzerstudie, die untersucht wie und wo Menschen auf ihrer Haut interagieren möchten. Die Resultate zeigen, dass verschiedenste Körperstellen für Interaktionen auf der Haut genutzt werden. Desweiteren ermöglichen Multitouch und für die Haut spezifische Modalitäten eine ausdrucksstarke Interaktion auf dem Körper.

Wir präsentieren drei auf der Haut getragenen Geräteklassen und ihre Interaktionstechniken, um ausdrucksstarke Eingaben auf dem Körper zu ermöglichen: *iSkin* erfasst Multitouch und unterscheidet zwei Druckstufen auf verschiedenen Körperstellen. *SkinMarks* erfasst das Berühren, Zusammendrücken und Dehnen der Haut und ermöglicht eine visuelle Ausgabe. Die speziell an die Haut angepasste Sensoren ermöglichen Interaktionen auf Körperstellen, wo Eingaben bisher nicht möglich waren. *ExpressSkin* untersucht ausdrucksstarke Interaktionstechniken, die auf hochaufgelösten mehrdimensionalen Druckeingaben basieren.

Damit ist diese Arbeit ein Schritt in Richtung ausdrucksstarker Interaktion mit Multitouch und für die Haut spezifische Modalitäten auf verschiedenen Körperstellen.

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Contents

1 | Introduction

Wearable computing devices, e.g. smartwatches and head-mounted displays, have seen an impressive growth in commercial products and public interest. They can be used for various computing tasks, e.g. for remote communication, entertainment, or to browse the internet. Their close contact to the body enables novel possibilities for mobile computing. For example, they are able to sense our movements and biosignals to allow for health and fitness applications. Beyond consumer electronics, specialized wearable devices can also assist workers of various industries [91].

The current generation of wearable devices uses touch as their primary input modality. Touch input is well suited for mobile interactions, because it allows for fast and direct interactions. It also allows for private interaction in mobile scenarios, because touch input requires only subtle movements that do not disturb people in our environments. Moreover, touch input has already proven its capabilities for mobile computing, as it is an established input modality for handheld devices, e.g. smartphones and tablets.

However, in contrast to handheld devices, current wearable devices trade-in the size of their interactive surfaces for wearability. Their smaller surface makes touch input highly challenging: The small size and the limited precision of touch input [169, 227] restrict the amount of supported interactive elements. This decreases the variety and quantity of actions a single touch contact can trigger on these devicess, i.e. they have a low input expressivity. As a consequence, wearable devices have to limit the set of possible actions or require additional navigation to select an action, e.g. scrolling. Furthermore, when the touch input is performed on a small wearable display, e.g. on a smartwatch, the finger occludes large parts of the display.

1.1 Skin as an Interactive Surface

A promising stream of research investigates on-skin input as a solution to the input problems of wearable devices. Instead of touching a wearable device, the input is performed on the user's skin. Skin is the largest human organ and therefore allows for interaction on a significantly larger surface than wearable devices. Many different body parts can be used for mobile interactions, such as the palm [34, 58, 59, 225, 226], fingers [20, 58, 85, 250], nails [95], arms [69, 122], back of the hand [121, 147], and ears [125].

Figure 1.1: Four application scenarios for on-skin input: (a) Occlusion-free input for smartwatches; (b) easy-to-access input surface for head-mounted-displays; (c) extending the input space of mobile devices; and (d) controlling displays outside of reach, e.g. televisions or public displays.

Similar to wearable devices, skin is easily accessible and supports fast interactions.

Using skin as an input surface for touch interaction has unique advantages: *Proprioception* helps to coarsely locate the input surface without visual feedback. *Tactile feedback* provides precise information about when, for how long, and where the touch occurs on the surface. The user feels the tactile cues through the receptors in his touching fingertip and the receptors in the touched skin. These tactile cues can replace visual cues and allow for *eyes-free interaction* [59].

On-skin interaction can allow for *single-handed input* that requires only subtle hand movements. This is especially important for mobile scenarios, because the interaction should be socially acceptable, ideally unnoticeable to avoid disruption of people in the surrounding, and not reveal private and sensitive information. For example, multiple commands can be mapped to the index finger and touched by the thumb of the same hand. Moreover, single-handed interaction can enable interactions while the hands are busy grasping objects.

Therefore, skin has great potential to act as an input surface for mobile and wearable devices. For example, it could enable occlusion-free input on the forearm next to a smartwatch (Figure 1.1a); fast and easily accessible input for head-mounted displays (Figure 1.1b); additional controls for handheld devices (Figure 1.1c); and remote control of remote displays (Figure 1.1d).

On-skin interaction is a relatively young research field in human–computer interaction (HCI). The proposed interactions mostly transfer touch interaction from handheld devices, e.g. tapping [69, 122] and multi-touch gestures [61]. However, skin is different from prior interactive surfaces: skin is soft, provides tactile feedback, and touching skin has strong emotional component [76].

Due to the differences to other surfaces, the interaction space of on-skin input remains largely unexplored:

1. The HCI community has few *empirical findings* that show how and where people want to interact on their skin and that detail on the users' mental models.

2. We lack technical enablers for precise touch sensing on *challenging body locations*. Prior prototypes limit themselves to slightly curved body locations. However, the body also contains many highly curved body parts and deformable skin areas. The tactile and visual cues of these locations have the potential to be beneficial for on-skin interactions.

3. Touch input contains more information than its contact location, e.g. contact size and exerted forces. These input modalities would allow for *expressive touch interaction* to increase the amount of executable actions. For example, a user interface could distinguish light and firm touch contacts to either move an item to the recycle bin or deleting it permanently. The HCI community currently lacks technical enablers and interaction techniques for such expressive on-skin input.

This thesis advances the field by contributing towards the *understanding of on-skin input* and by investigating thin, stretchable, and soft *on-skin devices*. They support challenging body locations and expressive interaction techniques.

1.2 Contributions of this Thesis

This thesis makes four contributions to the field of on-skin interaction:

1. Understanding Skin as an Input Surface

Skin is a promising input surface for mobile computing. However, it is fundamentally different from prior interactive surfaces: Skin is soft, provides tactile feedback, and touching skin has a strong emotional component [76]. Therefore, it is important to acquire knowledge of how people interact with this novel input surface.

We investigated how people use skin as an input surface by conducting an elicitation study. The study gives insights into the users' mental models during on-skin input. We analyze the characteristics of skin-specific input modalities, the gestures people perform on their skin, and detail on the participants preferred locations. We found that participants used different body locations to distribute and execute different input tasks. In addition, we found that skin has a dual character: people use traditional multi-touch gestures, as well as, novel skin-specific modalities. This allows for expressive on-skin interactions. For example, the subtle differences in touch, e.g. variations of contact forces, can be used to execute different actions.

Based on this empirical understanding, we contribute three interactive skin-worn device classes (see Figure 1.2). They enable expressive on-skin interactions in two ways: First, the devices expand the *supported locations* for on-skin input and enabled interactions on challenging body geometries. Second, the devices increase the *input expressivity* by supporting multi-touch gestures and novel skin-specific modalities.

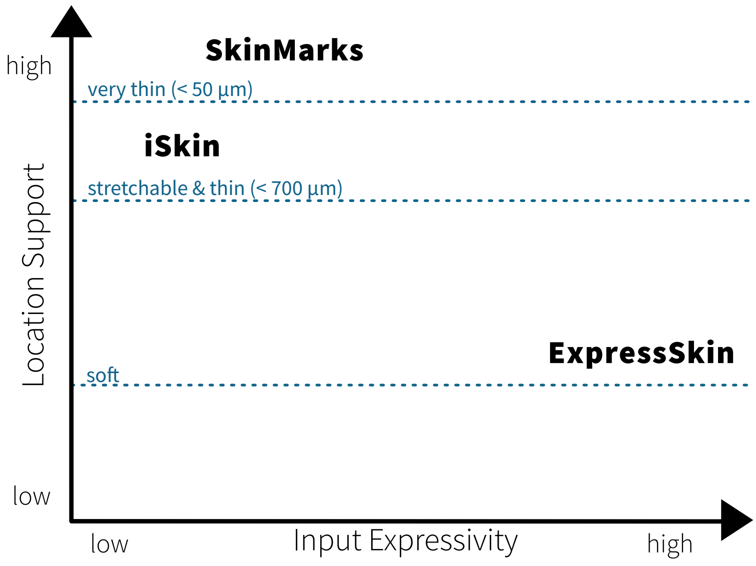

Figure 1.2: Device classes contributed in this thesis

2. iSkin: Touch Input on Various Body Locations

In our study we observed the use of various body locations to distribute interactive elements. However, the body is highly curved and the soft skin makes accurate touch input challenging. The primary goal of our first contributed device class is to expand the supported body locations (Figure 1.2).

iSkin enables precise touch interaction on various locations on the body. Its form factor allows iSkin to be worn on many locations of the body, e.g. around the highly curved finger or on the back of the ear. This is made possible, because iSkin is based on thin layers of biocompatible silicone. Therefore, iSkin is a touch sensor that is flexible and stretchable to be worn on the deformable skin.

The close proximity to skin allows for sensing touch input, including precise touch-down and touch-up events. iSkin senses two-levels of pressure by combining capacitive and resisitive touch sensing. Multiple touch-sensitive electrodes can form more complex widgets, such as sliders and click wheels. We show their use by contributing application examples. They show the versatility of iSkin in three types of skin-worn sensors that vary in their attachment: wraps around body parts, attachments to wearable devices, and adhered to skin.

In addition to our primary contribution, we identify design goals that outline important requirements and opportunities for skin-worn touch sensors. We recognizing visual aesthetics as an important dimension to improve social acceptability of skin-worn devices. Therefore, we contribute visual design patterns that allow to customize the visual appearance of functional sensors.

3. SkinMarks: Interaction on Body Landmarks

The human body has various types of landmarks, which are distinct from their surroundings and offer tactile and visual cues for interaction. These cues provide benefits for on-body interaction: they help in localizing interactive elements, guide touch input on the skin, and can help in memorization and recall of interactive elements. We contribute our definition of *body landmarks*: visual and tactile distinct locations on the body that can support and ease on-skin input. Based on this definition, we identify five types of body landmarks: skeletal landmarks, skin-microstructures, elastic landmarks, visual skin landmarks, and passive accessories. However, body landmarks have highly challenging geometries and narrow shapes, which are not supported in iSkin.

We contribute a second skin-worn device class, *SkinMarks*, to enable interactions on body landmarks. SkinMarks are interactive and highly conformal temporary rub-on tattoos. They are a magnitude thinner than iSkin sensors and enable interaction on challenging body locations. The main goal of SkinMarks is twofold (Figure 1.2): First, SkinMarks enables on-skin interactions on highly curved and small body landmarks and therefore expands the supported locations. We show that SkinMarks supports our five types of body landmarks and contribute interaction techniques that demonstrate their benefits. Second, SkinMarks extends the input expressivity of touch input. The skin-worn device enables precisely localized touch input on narrow body landmarks using sub-millimeter touch electrodes. Beyond touch contact, SkinMarks supports squeeze and bend sensing with integrated visual output.

4. ExpressSkin: Expressive Force-based Interaction Techniques

In our elicitation study, we found that skin-specific modalities, e.g. pressure, squeeze, and shear, allow for expressive on-skin input. Our forth contribution are interaction techniques that use force-based input modalities. To enable these interactions, we contribute *ExpressSkin*, a novel class of skin-worn devices. In contrast to iSkin and SkinMarks, its primary goal is to increase the input expressivity of skin-worn devices (Figure 1.2). As a consequence, ExpressSkin trades-in conformality for high-resolution force input. To ensure a high wearability on various body locations, ExpressSkin has a small and soft form-factor.

We contribute *interaction techniques* for force-sensitive skin-worn devices. The interaction techniques are based on continuous and high-resolution pressure, squeeze, and shear forces. They support fluid interaction in a large, multi-dimensional input space. We demonstrate our interaction techniques in six application examples, featuring single-handed and occlusion free input for smartwatches and subtle input for head-mounted displays. In addition, we contribute *findings of a user study* showing that ExpressSkin allows for precise and expressive interactions on many body locations, in standing and walking conditions.

1.3 Publications

Parts of this thesis have been previously published at conferences in the field of human–computer interaction. The main publications are three full papers [P1, P2, P3] and one journal article [P4] in the area of on-skin interaction:

P1. **Martin Weigel**, Vikram Mehta, and Jürgen Steimle. More Than Touch: Understanding How People Use Skin as an Input Surface for Mobile Computing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (ACM CHI '14)*.

P2. **Martin Weigel**, Tong Lu, Gilles Bailly, Antti Oulasvirta, Carmel Majidi, and Jürgen Steimle. iSkin: Flexible, Stretchable and Visually Customizable On-Body Touch Sensors for Mobile Computing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (ACM CHI '15)*. Best Paper Award (top 1% of submitted papers).

P3. **Martin Weigel**, Aditya Shekhar Nittala, Alex Olwal, and Jürgen Steimle. SkinMarks: Enabling Interactions on Body Landmarks Using Conformal Skin Electronics. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (ACM CHI '17)*.

P4. **Martin Weigel** and Jürgen Steimle. DeformWear: Deformation Input on Tiny Wearable Devices. In *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies, Vol. 1, No. 2*.

The research has been primarily published at ACM CHI [P1, P2, P3]. The interactive devices were demonstrated at ACM CHI '15 and CeBIT 2015. In addition to the main publications, the following list shows publications of relevant workshop papers, demos, and organized workshops:

P5. **Martin Weigel** and Jürgen Steimle. Fingernail Displays: Handy Displays at your Fingertips. In *CHI 2013 Workshop "Displays Take New Shape: An Agenda for Future Interactive Surfaces", 2013*.

P6. **Martin Weigel** and Jürgen Steimle. iSkin: Stretchable On-Body Touch Sensors for Mobile Computing. In *Mensch und Computer 2015: Interaktive Demos*.

P7. Jürgen Steimle and **Martin Weigel**. Praktische Einführung in gedruckte Elektronik für mobile, begreifbare und ubiquitäre Nutzerschnittstellen. In *Mensch und Computer 2015: Tutorial*.

P8. Joe Paradiso, Chris Schmandt, Katia Vega, Hsin-Liu Cindy Kao, Rébecca Kleinberger, Xin Liu, Jie Qi, Asta Roseway, Ali Yetisen, Jürgen Steimle, and **Martin Weigel**. UnderWare: Aesthetic, Expressive, and Functional On-Skin Technologies. In *Adjunct Proceedings of ACM UbiComp '16*.

1.4 Structure of this Thesis

This thesis is structured in seven chapters (see Figure 1.3):

- **Chapter 2** gives a background on human skin and empirical studies. First, it details on the anatomy of skin, its sense of touch, and body decorations. Afterwards, it presents prior findings from empirical studies about mobile interactions and interpersonal communication. Closing the gap in prior research, we present finding from our own empirical study. The study gives insights into the mental models of participants, the used on-skin gestures, and preferred locations on the upper limb. This empirical knowledge provides guidance for the design of on-skin sensors, novel interaction techniques, and applications. Based on this knowledge, we derive requirements and implications for on-skin interfaces. These build the foundation for the three novel touch-based on-body devices in chapter 4–6 and their interaction techniques.
- **Chapter 3** discusses the state-of-the-art in the field of wearable devices, on-body interactions, and thin-film electronics.
- **Chapter 4** presents *iSkin*, a novel class of skin-worn sensors that enable touch interactions on various body locations. It is a very thin sensor overlay, made of biocompatible materials. It is flexible and stretchable for a comfortable fit and robust sensing. Compared with commercial wearable devices, e.g. smartwatches, iSkin allows for larger input surfaces directly worn on the skin—the largest human organ. iSkin can cover various locations on the body and senses multi-modal touch input to support many interactions derived in chapter 3.
- **Chapter 5** presents *SkinMarks*, highly conformal skin electronics. They are based on very thin temporary rub-on tattoos and made for interaction on highly curved, deformable, and small body locations. They support touch, squeeze, and bend sensing with integrated visual output. Moreover, we define body landmarks: tac-

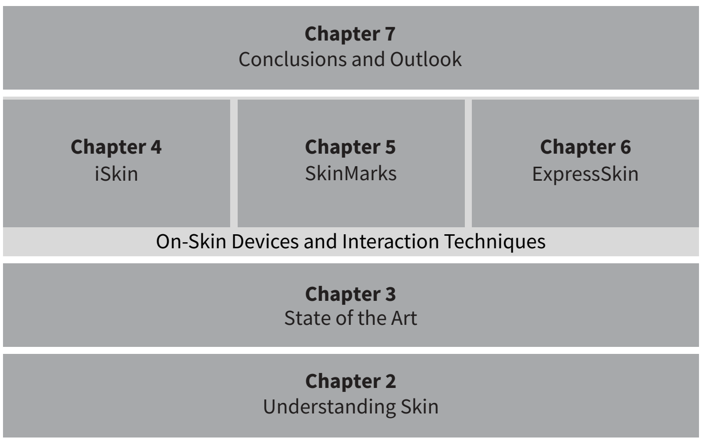

Figure 1.3: Structure this thesis

tile or visually distinct locations on the body that can be beneficial for on-skin input. We identify five types of body landmarks and demonstrate their benefits for on-skin interaction in application examples that we realized with SkinMarks.

- **Chapter 6** presents *ExpressSkin*. It investigates high-resolution force input on soft, skin-worn surfaces. The chapter proposes novel interaction techniques for skin-worn devices. They enable fluid interactions in a large multi-dimensional input space by combining continuous pressure, shear, and squeeze forces. We demonstrate ExpressSkin on three body locations and in six application examples. We conclude the chapter with a user study. Our findings show that force input is precise and expressive, in standing and walking conditions.
- **Chapter 7** summarizes the main findings of this thesis and shows directions for future work.

2 Understanding Skin as an Input Surface

Skin provides a large input surface, which is often easy to reach and fast to interact on. Therefore skin has great potential to act as an input surface for mobile devices. However, skin is fundamentally different from conventional touch surfaces. Since the physiological properties of skin vary across body locations, input location is likely to be very influential. Especially, since people have different mental associations with different parts of their body. Moreover, as skin is soft and elastic, it allows for additional input modalities, such as pulling, pressing, and squeezing. This increases the input space for on-skin interactions and enables more varied forms of interaction. Furthermore, interaction on skin has a strong personal and strong emotional component [76]. Such interactions could enable a more personal way of interaction. This opens up a new interaction space, which is largely unexplored.

This chapter aims to contribute to the systematic understanding of skin as an input surface. First, we describe the structure and properties of human skin from an anatomical perspective (Section 2.1). Second, we present prior studies about touch interaction on the skin (Section 2.2). It will cover studies in human–computer interaction on performance and social acceptability of on-skin input, as well as, studies on interpersonal communications. Third, we detail on the findings of our elicitation study (Section 2.3). Finally, we summarize the findings and derive the two main themes of this thesis.

2.1 Background on Human Skin

Skin is the boundary of our body to the environment. It is the largest human organ of adults with an average surface area of $2\,\mathrm{m}^2$. On average, it is around 2.5 mm thick and weights around 5–6 kg [76]. Skin has two main functionalities: First, it works as a barrier to the environment. It regulates what enters and exits our body and protects the body from various kinds of damage (e.g. radiation, bacteria, and chemicals). Second, it allows for sensing the environment through tactioception (i.e. touch) [76].

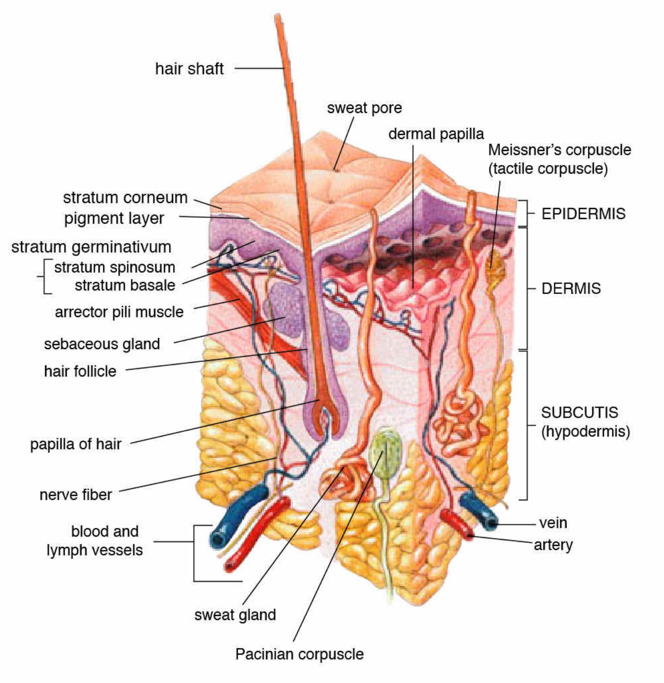

Figure 2.1: Structure of the skin (source: US-Gov, under public domain)

2.1.1 Anatomy and Physiology

Human skin is composed of three main layers (see Figure 2.1): epidermis, dermis, and hypodermis. This section briefly describe properties and functions of each layer.

The *epidermis* is the layer that will be touched during on-skin interaction. It is the outermost layer of skin, which forms the boundary between the body and its environment. The epidermis provides a barrier against environmental infections and regulates the transepidermal water loss. The total thickness of the epidermis varies between different body parts. It can be very thin ($\approx 50\,\mu m$) and forms thicker protection on the palms, fingers, and foot soles ($547\,\mu m$–$1159\,\mu m$) [76]. The epidermis is also responsible to block UV light by producing melanin. This melanin can creates age spots, freckles, and birthmarks. These can be used as visual cues for on-skin input, as we demonstrate in chapter 5. The major cell type of the epidermis is keratinocyte [142]. These cells die on the outermost layer and form a physical protection of the skin.

Below the epidermis is the *dermis*. The dermis is an dense irregular connective tissue that absorbs shocks and therefore cushions the body from external stresses [76]. Its thickness varies between 1 mm to 2.5 mm on average. It provides strength to the skin through a network of fibres [206]. Collagen fibres give tensile strength to the skin and elastic fibers allow for its elastic recoil. This allows for skin-specific input modalities that deform the skin, e.g. pulling and twisting. Both, strength and elasticity, depend on the body location and can vary between people. Moreover, local breakdowns in collagen create wrinkles on the skin, which can be used as tactile guides during touch input (see Chapter 5). The dermis contains hair follicles, lymph and blood vessels, as well as, sweat and sebum glands. In addition, it contains most sensory cells of the skin [54]. These cells are able to detect pressure, touch, vibration, temperature, and pain. Therefore, they allow for sensing of expressive tactile cues.

Under the dermis lies the *hypodermis* or subcutaneous tissue. This layer is used for fat storage and connects the blood and lymph vessles with the rest of the body.

2.1.2 Sense of Touch

Skin plays an important role in our tactile perception, i.e. the sense of touch. This allows us to feel tactile cues during on-skin input with our fingertip and the touched surface. The tactile feedback allows for on-skin interaction without visual attention [59]. Skin contain four types of *mechanoreceptors* that sense different types of touch. The four receptors are Merkel cells, Meissner corpuscles, Vater-Pacini corpuscles, and Ruffini corpuscles.

- *Merkel cells* are the most outer mechanoreceptors and can be found in the epidermis [108]. They sense small deformations of the surrounding layer of keratinocytes. Some body parts have a high concentration of Merkel cells, e.g. the fingertips and lips. This allows for a very high tactile sensitivity.
- *Meissner corpuscles* are tactile corpuscles found in the uppermost layer of the dermis. They help to mediate light touch. They have the highest density on the hands, especially the fingertips [108].
- *Vater-Pacini corpuscles* are located in deeper levels of the dermis. They create a sense of vibration and detect changes of pressure [108]. However, they only can tell a change in the signal, e.g. the beginning and end of a pressure, but do not give information on sustained pressure.
- *Ruffini corpuscles* are slowly adapting mechanoreceptor that sense stretch of skin, sustained pressure on the skin, and provide a perception of heat.

Since these mechanoreceptors vary in their density across the body, different body parts have a different resolution for touch sensing. For example, the hand has a high density of receptors with approximately 17.000 mechanoreceptors [92]. Its density is varying across different parts of the hand: Fingertips have the highest density with a spatial resolution of of $0.59\,\text{mm}^{-1}$, compared to $0.26\,\text{mm}^{-1}$ on the finger shafts, and $0.13\,\text{mm}^{-1}$ inside the palm [217]. The spatial resolution of touch correlates with the density of Merkel cells and Meissner corpuscles in those body parts, which suggests these mechanoreceptors have most influence on the spatial acuity [217]. Hence, interaction on the fingers yield the highest tactile feedback. Based on this knowledge, our example applications in chapters 4–6 include examples of finger-worn devices for eyes-free and single-handed input.

Besides mechanoreceptors, *thermoreceptors* throughout the skin sense warm and cold temperatures. These receptors do not only detect ambient temperature changes, but can also detect localized temperature differences. For example, a person can feel the temperature difference when he is touched by a cold hand. Thermoreceptors could allow for haptic feedback by controlling the temperature of a skin-worn device.

2.1.3 Personal & Aesthetic Body Decorations

The body has been modified in cultural groups through human history. They are performed “in an attempt to meet their cultural standards of beauty, as well as their religious and/or social obligations” [29]. They can be either removable (body adornments) or permanent (body modifications). Easily removable body adornments include jewelry, hair styling, henna tattoos, nail-art, and make-up. Permanent or hard to remove body modifications include tattoos, piercings, tunnels, and implants. For example, tattoos consist of color particles into deeper into the skin, i.e. the dermis [114], which are challenging and painful to remove.

In more recent years, body modifications have been mostly performed for aesthetic reasons. They are used as an “expression of the self” [213], for self-creation, demonstrating individualism, or as a permanent, personal diary. This shows that skin is a highly personal canvas and that body-worn accessories should allow for personal and aesthetic modifications of their visual appearance. The aesthetic importance of wearable devices has been also identified and investigated by Vega and Fuks [220]

2.2 Empirical Studies on Skin Interaction

As shown in the last section, skin is fundamentally different from other interactive surfaces. Prior work conducted first empirical studies to understand on-skin touch input for mobile computing and interpersonal communication. Their findings form an important foundation for this thesis: They demonstrate the performance and social acceptance of basic touch input, both important aspects to enable expressive on-skin interaction. Furthermore, they show that touch allows for expressive interpersonal communication, which can inspire novel interactions for mobile computing.

2.2.1 Touch for Mobile Interactions

The performance and social acceptance of touch input on the body has been investigated in multiple user studies. Wagner et al. [223] investigated pointing performance and user preferences of touching different body locations (Figure 2.2a). Their findings show that touching the upper limb has the highest social acceptance and was rated positively by the participants. Performance-wise, the mean pointing time on the upper limb was faster than on locations on the lower body, but slower than on the torso.

Other pointing studies revealed that people are able to reliably distinguish different areas on the body. Hence, the large surface of the skin can be used to distinguish dif-

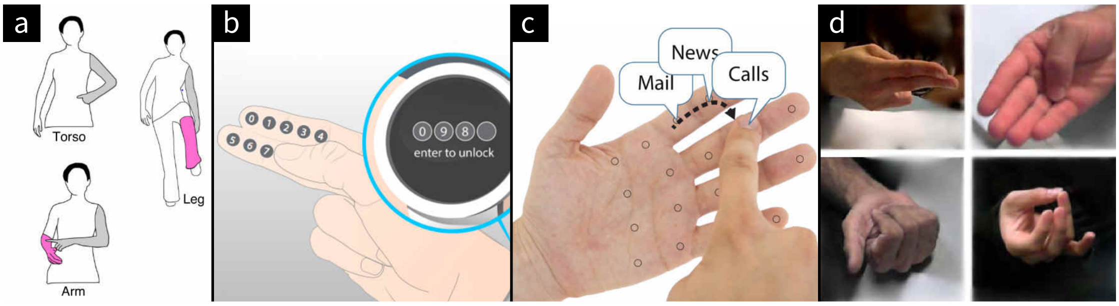

Figure 2.2: Studies on touch input: (a) on-body pointing [223], (b) input on the finger [85], (c) palm-based imaginary interfaces [59], and (d) single-hand microgestures [17].

ferent interactive elements, e.g. icons and buttons. They found a maximum of eight to ten locations on their forearm with and without visual cues [69, 122]. Findings of Dezfuli et al. [34] show that users can interact on nine touch areas of the hand without visual attention. Wang et al. [225] extend this concept by mapping 26 keyboard characters to the palm. Without visual attention, their results show a 39% faster input on the palm than on a touchscreen. Huang et al. [85] evaluated comfort and accuracy of touch input on the finger and suggested a layout with 16 buttons. They further investigated gestures on the fingers and found significant different stroke paths than on rigid, flat surfaces. Bergstrom et al. [9] show that skin allows for an average recall of 21.2 (out of 30) items.

Prior studies investigated the usability of tactile feedback for on-skin input. Findings of studies on palm-based imaginary interfaces show that people can effectively interact on skin without visual output. A first study demonstrated that users are able to point to imaginary icons on their palm by leveraging spatial memory from prior interaction with a smart phone [58]. A further study revealed that when users are blindfolded, tactile cues can replace visual cues for precise pointing on imaginary interface elements [59] (Figure 2.2c). Oh and Findlater [157] studied basic pointing performance and gestures for people with visual impairments. They confirmed that input on the hand has a higher performance than input on a phone for non-visual use. They also found that palm-based input has a better first contact success rate and that gestures on the palm have higher recognition rates. Palm gestures with no visual feedback were also investigated by Wang et al. [226]. Their findings show that participants prefer using the whole palm as input surface and that they use three hand orientations: horizontal, diagonal and vertical.

Profita et al. [172] studied the social acceptability of on-body input in the United States and South Korea. They found the best perceived social acceptability on the wrist and forearm across cultures. Input on pockets and the waistline was less acceptable for men, while input on the collarbone and torso were less acceptable for female users. This suggests a gender effect that should be considered for the placement of body-worn input devices.

The difference of skin compared to other surfaces challenges traditional input paradigms.

However, the human–computer interaction community lacks an understanding of how and where people want to interact on their skin. Therefore, we conducted an elicitation study to understand on-skin interaction on the upper limb (see Section 2.3). This approach was inspired by prior elicitation studies [118, 243]. These studies investigated other novel interfaces, i.e. tabletops [243] and deformable displays [118], and allowed to gain qualitative insights into the participants' behavior, as well as, their preferred gestures and locations. Other researchers elicitated gestures performed in the face [195]. Their study focused on gesture input for head-mounted displays, their performance, and social acceptability. Oh and Findlater [156] elicitated on-skin gestures for people with visual impairments. They found that the hands were considered to be more discreet and natural than forearm, face, and neck. Moreover, their findings show that participants may prioritize social acceptance over comfort and ease of use. More recently, Chan et al. [17] investigated single-hand micro-gestures in an elicitation study (Figure 2.2d). In contrast to our study, these gestures enable one-handed input, but are limited to the smaller input surface of the same hand.

Findings on visual output on the skin show where to locate visual feedback. In a first study, Harrison et al. [67] evaluate reaction time performance of visual feedback on seven locations. Their participants had the fastest average reaction time performance on the wrist and arm. In a second study, Harrison et al. [62] studied where to project on-body interfaces. Using crowd-sourcing and expert interviews, they found that hands and arms are the most social acceptable areas. They also found the tights an appealing surface for projection, due to their easy accessibility while sitting. However, this area is usually covered by clothing and is less usable while standing and walking.

2.2.2 Touch for Interpersonal Communication

Another research stream studied the characteristics of touch for interpersonal communication. Although such gestures have not been used to control mobile devices, we observed some of these gestures in our elicitation study. Hence, their findings play role for on-skin interactions, because they show possible gestures and mental models.

Studies of interpersonal touch highlighted that people can distinguish various types of touch [93]. In two studies with blindfolded participants, Hertenstein et al. [73, 75] found that participants were able to communicate an emotion to another person via touch. In the first study [75] a stranger touched another participants arm to communicate a specified emotion. The findings show that participants were able to communicate six emotions with above chance-level. In the second study [73] participants could freely choose the location they touched. The findings show that participants were able to communicate eight emotions in a robust fashion. The touch is not purely contact based, but adds many other modalities, e.g. pushing, pulling, and shaking. Further evaluation of the data shows that male and female participants communicate different emotions better than the opposite gender [74]. In total, the average accuracy in both studies was similar to facial displays and vocal communication. This demonstrates that touch is an expressive form of interpersonal communication.

To sum up, prior studies show a great potential for skin as a user interface, especially on the upper limb. On-skin input allows for multiple commands by mapping touch elements to distinct locations on the skin. The study findings reveal good pointing performances and a rich tactile feedback, allowing for eyes-free input. Furthermore, they suggest that interpersonal touch provides a rich, yet unexplored, gesture set for on-skin input. The next section will elaborate on the findings of the elicitation study, detail on skin-like input modalities, and the users' mental models.

2.3 More Than Touch: Understanding How People Use Skin as an Input Surface for Mobile Computing

Prior studies investigated the performance and social acceptability of pointing or tapping on skin. They help to understand traditional input methods from handheld devices on the novel input surface, i.e. skin. These studies assume that people interact on skin the same way as on flat and rigid handheld devices. However, the soft skin allows for novel input modalities, e.g. skin can be deformed, and its emotional component might influence the user's mental models. Therefore, it is important to acquire knowledge of how people interact with this novel input surface to understand if traditional input methods transfer or if, and to which extend, novel input modalities are used on the skin.

This section contributes results from the first study on multi-modal on-skin input [1]. It empirically addresses on-skin input from three main perspectives, which impact the usability and the design of future sensors and applications:

- What are characteristics of skin-specific input modalities? What modalities do people use?
- What kinds of gestures do users perform on their skin for mobile computing? What are the mental models associated with them?
- What are preferred locations on the upper limb for touch-based interactions?

These findings provide guidance for the device classes and interaction techniques of this thesis (Chapter 4, 5, and 6). In addition, they can guide researchers and practitioners in developing future sensors, in designing novel interaction techniques, and implementing applications for on-skin input.

2.3.1 Methodology

The study followed an elicitation methodology similar to Wobbrock et al. [243]. This approach has proven successful in prior work on a range of novel interfaces [118, 243] for providing "insights into users' mental models" and "implications for technology and

[1] This section is based on a publication at ACM CHI'14 that I led as a main author [235]. I led the design and evaluation the study. I conducted the study and parts of the analysis together with my co-authors.

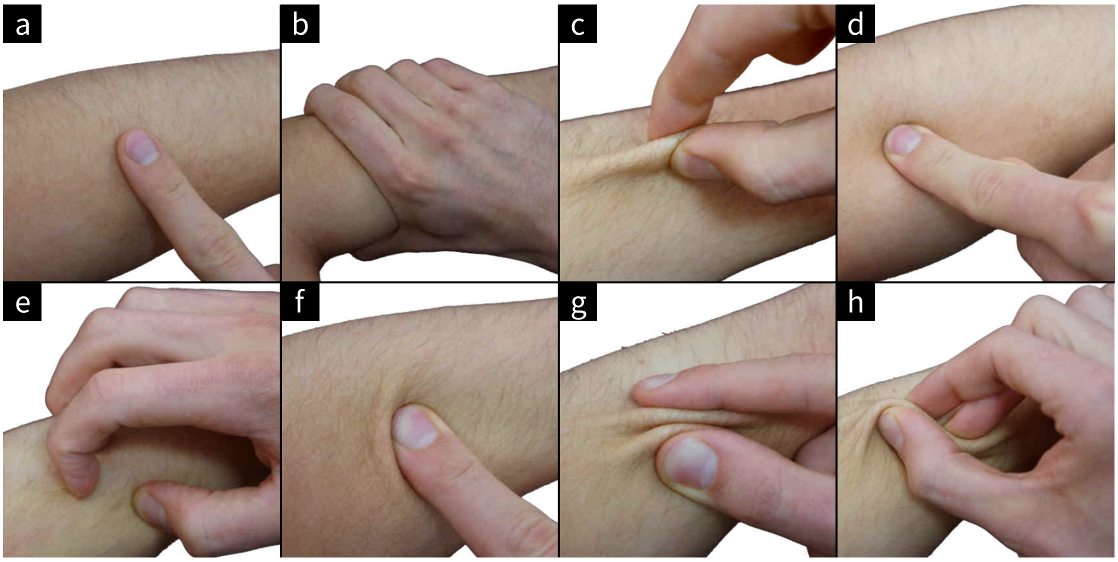

Figure 2.3: Input modalities: (a) touch, (b) grab, (c) pull, (d) press, (e) scratch, (f) shear, (g) squeeze, and (h) twist

UI design" [243]. In addition to eliciting gestures for a set of standard commands, we elicited gestures for an extended set of commands for mobile computing as well as for emotional expressions. This accounts for the expressive nature of skin. Moreover, we elicited mappings to specific on-skin locations. In addition, we systematically investigated ease and comfort of input modalities across locations. We opted for not using any specific sensing technology and not providing any form of output. This allowed us to investigate the full input design space independently of constraints that would be imposed by present-day technology.

Input Modalities and Body Location

The flexible nature of skin affords not only touching, but also pulling, shearing, squeezing, and twisting. Skin is capable of sensing various levels of contact force, which enables pressing. Lastly, the physiological properties of the touching finger or hand further add to the expressiveness: touch can be performed with the fingernails, resulting in scratching, or the full hand can enclose another body part, resulting in grabbing. The resulting set of eight modalities is shown in Figure 2.3. It was derived from established modalities of conventional touch interfaces and from results of studies on the biomechanics of skin [1, 72]. These modalities are ranging from on-surface interaction to intense skin deformations. More complex gestures, e.g. rubbing or shaking, can be performed by using these basic input modalities. Note that these modalities are defined from a user perspective and not from a technology-centered one.

For keeping the study focused, we restricted input to the upper limb. This is the location used in almost all previous work [34, 58, 59, 61, 68, 69, 122, 161, 175, 186]. It is socially acceptable for input [223] and less likely to be covered by clothing than most other body parts. Based on the anatomy of the upper limb, we divided it into six distinct locations

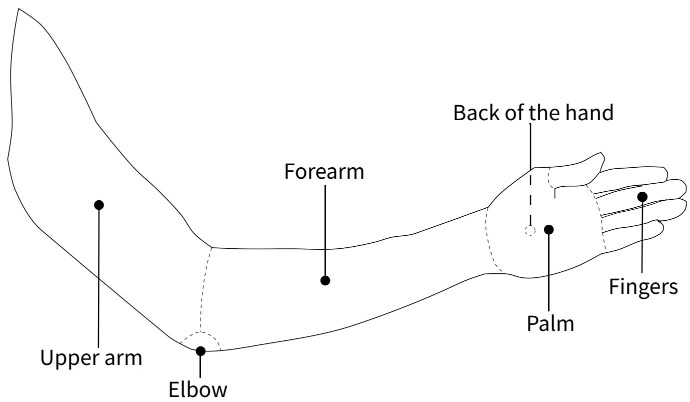

Figure 2.4: Locations on the upper limb

(Figure 2.4), which differ in their range of motion, their flexibility, and their boniness. We excluded the shoulder, as this is typically covered by clothing.

Participants could freely choose between the dominant and the non-dominant upper limb for performing input. They were seated at a desk and did not hold anything in their hands. Participants who wore long-sleeved clothing turned both sleeves up, such that skin on all locations below the shoulder was uncovered and freely accessible.

Tasks and Procedure

Participants were asked to perform input directly on their bare skin without any instrumentation of the body, to preserve tactile feedback. As existing sensor hardware can capture only some few of the input modalities that are possible on skin (see Chapter 3), we opted for not using any specific sensing technology. This allowed us to observe participants' unrevised behavior, free of the restrictions of current hardware. This method prove helpful in previous work for deriving implications for future hardware and system designs to accommodate this user behaviour [118, 243]. Moreover, to avoid biasing participants by a specific form or location of output, we opted against providing any system output.

The study comprised three tasks, in a single-user setting:

Task 1 (T1). This task was designed for investigating properties of on-skin gestures. The participant was sequentially presented 40 different referents. For each of them, the task was to invent a corresponding gesture and perform it anywhere on the skin of his or her upper limb. Figure 2.5 gives an overview of all referents. We selected referents from prior work [118, 243] and added standard commands for mobile scenarios and variations for some referents (e.g. deleting temporarily vs. deleting permanently) to analyse how more subtle differences influence on-skin input. Inspired by the human ability to express emotions through touch [73, 75], we added a set of emotional

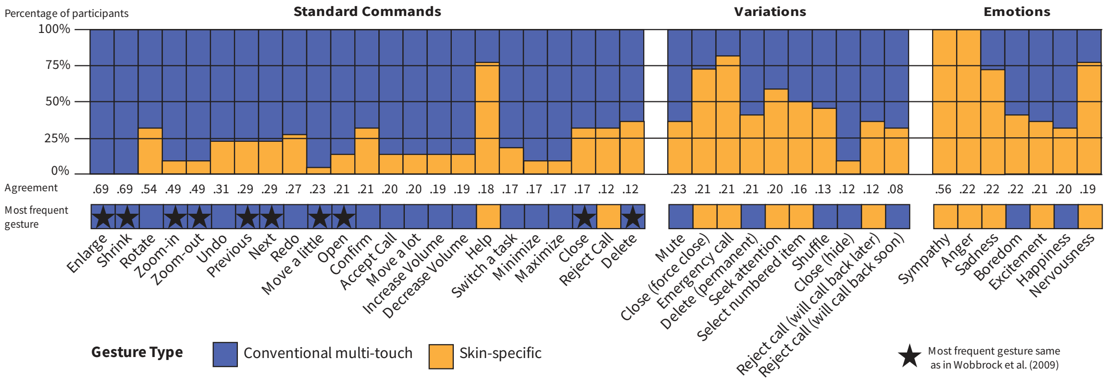

Figure 2.5: Overview of user-defined gestures

expressions covering all four main classes on Schacter's two-dimensional spectrum of emotions [188]. These emotional expressions could support a more personal way of input for remote communication. They could also support novel ways of interacting with computer contents through affective computing [167], e.g. for liking or disliking media items.

Task 2 (T2). This task specifically focused on usability of input modalities across different locations on the upper limb. The participant was asked to perform input using each of the 8 modalities introduced above on the six different locations. For each of the combinations, the participant rated the perceived ease of use and comfort of use on two five-point Likert scales.

Task 3 (T3). This task was designed to investigate other forms of input than gestures. We presented a set of input types derived from established interactions with mobile devices (Table 2.2 on page 26), e.g. text entry on a virtual keyboard. We asked the participant for each of them sequentially what is the location on the upper limb where they would intuitively most like to provide input for the input widget. We also investigated how participants arrange virtual items using different orders and levels of privacy (see Table 2.1 on page 25).

The study followed a think-aloud protocol to obtain rich qualitative data of the mental models of the participants. We specifically encouraged participants to verbally describe the gestures they performed and to describe their reasoning as accurately as possible. To avoid bias, the order of items was randomized in each task. Moreover, the order of T1 and T2 was counterbalanced. T3 was performed as last task, to avoid biasing the intuitive choice of location in T1.

At the end of each session, we conducted a semi-structured interview and handed out a questionnaire to collect demographic data. Each session took around 70 minutes and was video-recorded. We collected a total of 880 gestures (40 referents per participant) during T1, 1,056 ratings of input modalities (48 per participant) in T2, and 198 location preferences for input widgets and orders (9 per participant) during T3. We used grounded theory [44] for the qualitative analysis of the dataset.

Participants

22 voluntary participants (11f, 11m; mean 25.3y; median age 24.5y) were recruited for the study. Each received a compensation of 10 Euros. 18 participants were right-handed, 2 left-handed, and 2 mixed-handed. Participants had various cultural backgrounds (Europe, Middle East, North Africa, India, Far East). Their occupations included teacher, editor, researcher and students in biology, education, law, computer science, tourism, and psychology. All participants were frequently using computing devices. Seventeen participants owned a device with a touch screen.

In the following, we investigate what kinds of gestures participants have defined. Are they similar to gestures from conventional multi-touch devices or specific to the affordances of skin? We discuss their characteristics as well as the reasons for performing skin-specific gestures. This is followed by an investigation of what are preferred input locations on the upper limb and what meanings are associated with different locations.

2.3.2 Multi-touch vs. Skin-Specific Gestures

In our analysis, we manually classified each user-defined gesture qualitatively using the following dimensions: input modalities, location on the body, and properties of the gesture (pressure, speed, direction, repetition, contact area). In a second step, two authors separately classified each gesture as skin-specific if it incorporated at least one input modality other than multi-touch or if the participant had explicitly mentioned a skin-specific reasoning when performing a multi-touch gesture. The remaining gestures were classified as conventional multi-touch gestures.

We calculated the Cohen's Kappa coefficient to measure the inter-rater agreement:

$$\kappa = \frac{p_o - p_e}{1 - p_e}$$

where p_o is the observed agreement and p_e is the probability of random agreement. The calculated Cohen's Kappa was 0.746, indicating a substantial to excellent agreement on the definition.

Figure 2.5 depicts main results for all referents of the three gesture sets of task 1 regarding the distribution between skin-specific gestures and conventional multi-touch gestures. It also gives the agreement score A_r for a referent r as defined by [243]:

$$A_r = \sum_{P_i \subseteq P_r} \left(\frac{|P_i|}{|P_r|} \right)^2$$

where P_i are the subsets of identical gestures performed for a referent.

Our scores are comparable with those in prior work [118, 243] despite the larger input space of our study. While the set of standard commands involved only an average of 21% of skin-specific gestures, the variation set comprised 46%, and the emotional set 66%. An ANOVA identified significant main effects between these sets ($F(2, 63) =$

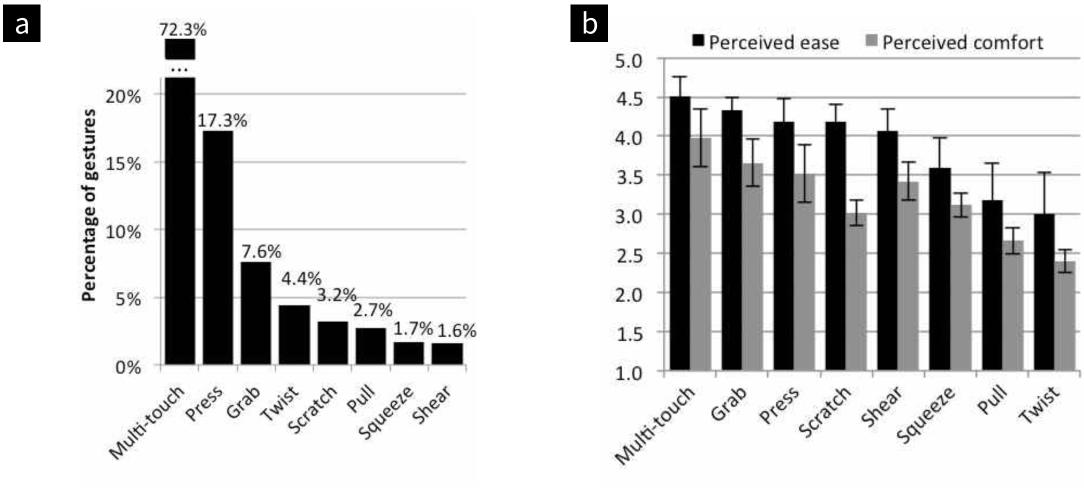

Figure 2.6: Input modalities: (a) Modalities used in the user-defined gestures. (b) Aggregated means and 95% confidence intervals of perceived ease and comfort.

$39.68; p < 0.05$). Bonferroni corrected post-hoc tests found significant differences between all sets. In-line with this finding, we identified a monotonous increase in the number of referents, for which the most frequent gesture was skin-specific: this held true for only two referents in the standard set, but for 5 of the 10 referents in the variation set, and even for 5 out of the 7 referents in the emotional set.

To characterize usage of input modalities, Figure 2.6a depicts for each modality the percentage of all user-defined gestures that involved this modality. Multi-touch is used in 72.3% of all gestures. It is very likely that the higher familiarity of multi-touch gestures partially influenced these results. However, even despite the novelty of skin-specific modalities, they were consistently used for expressive interactions. The most frequently used skin-specific modalities were pressing and grabbing.

Even though participants were allowed to use any hand for interaction, all preferred to interact with the dominant hand on the non-dominant upper limb. Mixed-handed people switched between both hands.

Standard Commands

Most gestures performed for referents in the standard set were conventional multi-touch gestures. For ten referents of the standard set, the most frequent gesture was identical with the one found by Wobbrock et al.'s study of touch surface gestures [243]. These findings show that participants transferred conventional multi-touch gestures to on-skin input. Only two referents in the standard command set had a most frequent gesture that was skin specific: 'Help' and 'Reject call'. These outliers will be discussed in section 2.3.3.

Variations of Standard Commands

For variations, participants used skin-specific gestures more frequently. The most frequently performed gesture was skin-specific for five of the ten referents.

Figure 2.7a gives an overview of important skin-specific gestures, which we identified for standard commands and for their variations. Some of them were the most frequent gesture performed for the respective command; some were skin-specific alternatives to the most frequent multi-touch gesture. We included only alternatives for commands where the most frequent skin-specific gesture was performed by at least three participants. We opted against depicting the most frequent multi-touch gestures, since these were in-line with the findings reported in [243].

Emotional Expressions

Participants used a skin-specific gesture for the majority of emotional expressions. In the semi-structured interviews, all participants stated that they could express emotions better on their skin than on a touch screen. One main reason was that this allows them to draw inspiration from typical ways of expressing emotions when touching other people. Only happiness and boredom turned out to be easier to express with multi-touch gestures. Here, people took inspiration from facial expressions (smiley) and bored tapping on a surface.

Figure 2.7b shows a conflict-free user-defined gesture set for all emotional expressions. For each expression, it contains the most frequently performed gesture. Following [243], whenever the same gesture was used for different emotions, the conflict was resolved by assigning it to the larger group and selecting the second most frequent gesture for the smaller group.

In conclusion, our findings show that conventional multi-touch gestures for standard commands are transferred from touch screens to on-skin input. Skin-specific gestures are preferred for expressing emotions. They are also frequently used for expressing variations of a command.

2.3.3 Reasons for Using Skin-Specific Gestures

Skin-specific gestures were used less frequently than multi-touch gestures, but added expressiveness. The analysis of the user-defined gestures revealed two main mental models, which explain why participants opted for using skin-specific gestures:

Inspiration from Touch Interactions with Other People

Most gestures performed for emotional expressions were inspired from how one touches another person to convey emotion. To express sympathy, 73% of participants rubbed or stroked their arm, as if they consoled another person. “I would console someone in real-life situations like this.” [P7]. To express anger, six participants hit their palm with the fist, five grabbed and squeezed their skin, and others used twisting or scratching.

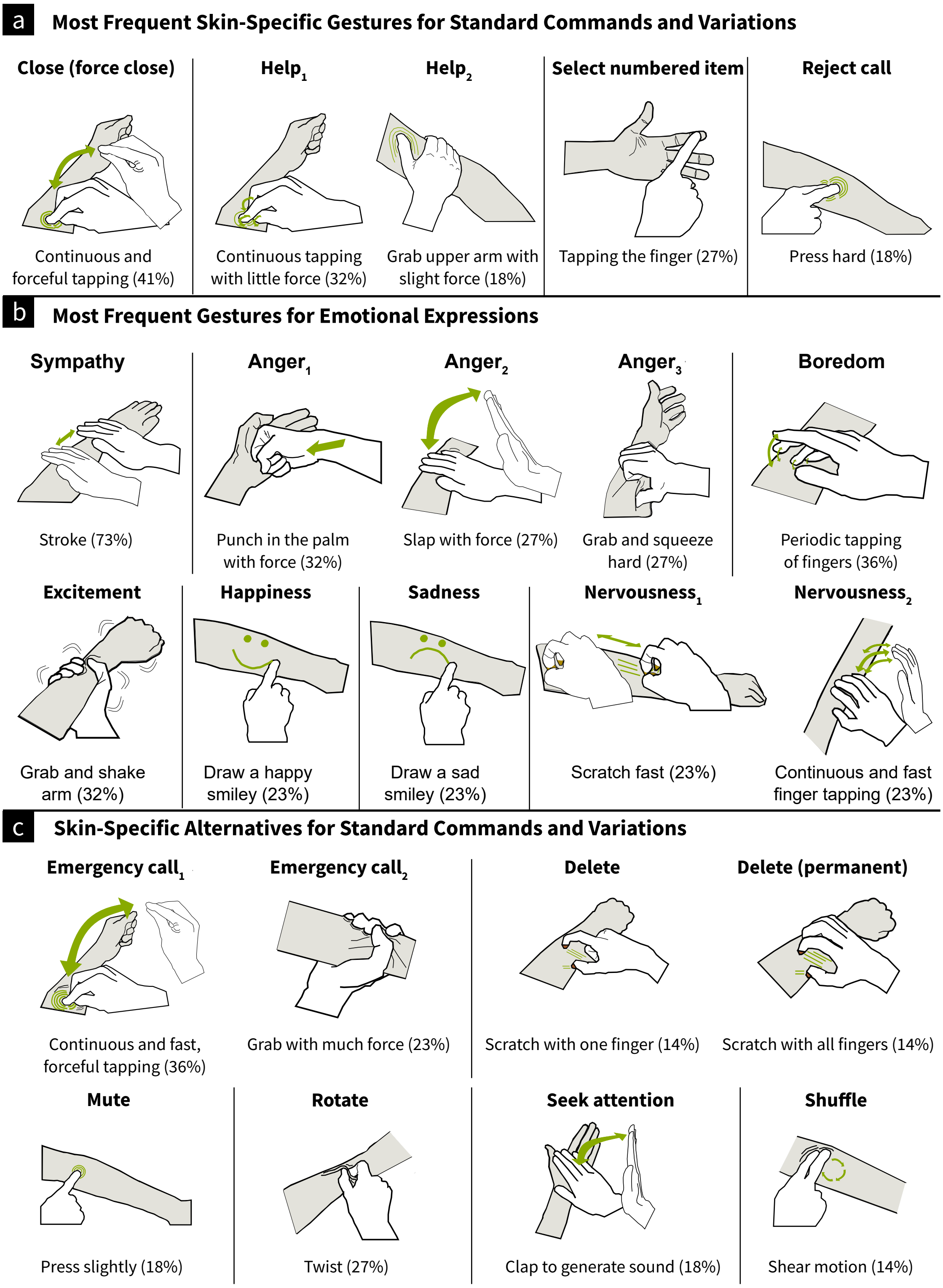

Figure 2.7: User-defined set of skin-specific gestures

However, also conventional computer commands were inspired by interactions with other people. For help, 32% of participants performed a poking gesture, as if they poked a nearby person. Another common gesture was grabbing their upper arm, as if they grabbed another person. P20 stated that this is the touch gesture she would use to approach another human to ask him for help: "If I imagine a person I would grab him here [pointing to her upper arm]." Also ten participants seek attention either by making a sound using clapping to "direct the attention of the person to myself" [P2] or by poking the person virtually through their own arm as if they said "Hey, there!" [P7] while "tapping the person on the shoulder" [P7].

Leveraging Physical Affordances of Skin

Participants made use of tactile feedback and leveraged the expressiveness of skin modalities and locations. For instance, 27% of participants used twisting for rotation due to the affordance involved: "It feels like actually grabbing the object and rotating it" [P4]. 45% of participants varied the pressure for distinguishing between temporary close and force close; the latter gesture was performed with much stronger pressure, which provides a distinct tactile feedback. Affordances of specific body locations were also leveraged for selection: 36% of participants touched one of their fingers of the non-dominant hand to select a numbered item.

These mental models show that skin-specific interaction has great potential to enhance the user experience of on-skin input. Participants used skin-specific modalities to add expressiveness to their gestures and mimic established interpersonal gestures. These gestures can be taken as a source of inspiration for on-skin gestures to encourage users to interact in a more personal way with electronic devices.

2.3.4 Perceived Ease and Comfort of Use

To gain a systematic understanding of how people perceive these gestures, we asked them to rate eight different input modalities (Figure 2.3) performed on six different locations (Figure 2.4) on the skin of their upper limb. They rated perceived ease and comfort of use on two independent Likert-scales. The aggregated results for input modalities across all six locations are given in Figure 2.6b.

All input modalities were perceived as being rather easy to perform. The means for perceived comfort of use followed the same order, with somewhat lower means. The only outlier was scratching. This is explained by qualitative feedback: although participants did not perceive scratching as physically uncomfortable, it was perceived as a socially unaccepted and awkward input modality: "I feel like a monkey" [P19].

Figure 4b shows a clear relation between perceived ease/comfort of use and the degree to which skin is deformed: the more the input modality deforms the skin, the lower its rating. Multi-touch, grabbing, and pressing have the highest means. This corresponds to the order of frequency in which participants have used these modalities in their user-defined gestures. While multi-touch was the most frequently used modality, it was followed by grabbing and pressing, in this order (see Figure 2.6a).

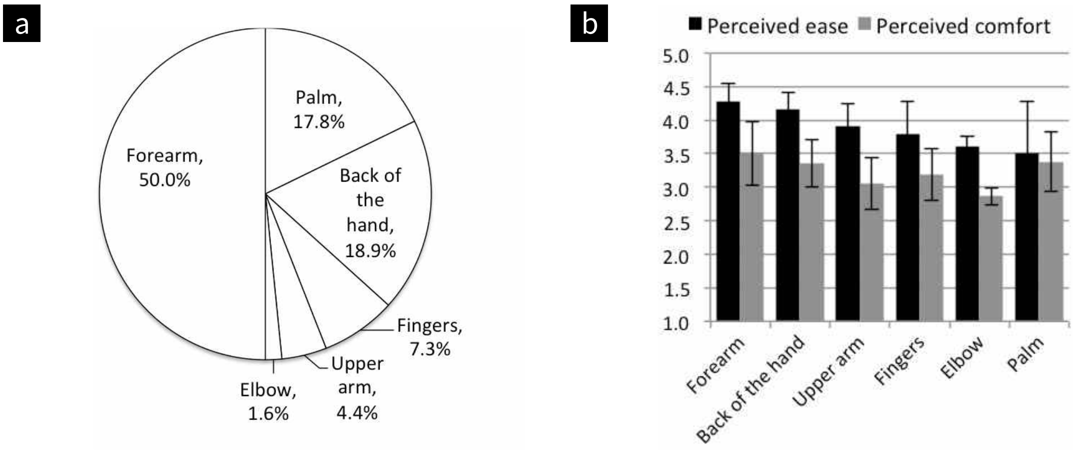

Figure 2.8: (a) Locations of user-defined gestures. (b) Means and 95% confidence intervals of perceived ease and comfort.

The modality with the lowest mean ratings, both in ease and in comfort of use, was twisting. Interestingly, this modality was used much more frequently in user-defined gestures than scratching, shearing, squeezing, and pulling, even though these latter modalities had higher ratings. This finding will be discussed in the next section.

2.3.5 Deliberately Uncomfortable Input Modalities

Surprisingly, participants deliberately chose uncomfortable input modalities to perform some specific commands. This involved quite intense pressing, pulling, twisting, and squeezing, which created some slight sensation of physical pain.

Uncomfortable interactions were chosen for actions that are very important and not reversible, e.g. permanent deletion (32% of participants) or force close (23% of participants). They ensured a higher degree of consciousness while performing the action: "You have to be conscious while deleting" [P22]. Participants also used uncomfortable gestures to express intense emotions, e.g. anger, even though they were interacting with their own skin instead of the skin of another person. Participants stated: "It needs to hurt to express anger" [P2] and "it should hurt" [P6], while they were twisting or squeezing their skin to express anger. However, participants mentioned that the gestures were performed "more gently than I would on another person" [P6].

These results add to the understanding of how uncomfortable interactions can improve user experience [8].

2.3.6 Input Locations

All three tasks allowed us to investigate characteristics of input locations on the upper limb. Figure 2.8a shows the locations where user-defined gestures were performed.

Order	Concept
Frequency	Close to the hand (86% of participants)
Importance	Close to the hand (64% of participants)
Liking	Close to the hand (68% of participants)
Privacy	Private on inner side; public on outer (all)

Table 2.1: Orders of T3 and their most preferred locations

Half of all gestures were performed on the forearm. Also the back of the hand and the palm were frequently used location, while the upper arm and elbow were rarely used.

Figure 2.8b shows the mean values for perceived ease and comfort of use for each location, aggregated for all input modalities. As expected and in-line with Figure 2.8a, the forearm showed the highest perceived ease and comfort of all locations, followed by the back of the hand. Surprisingly, the palm received the lowest value for perceived ease, contradicting to the findings depicted in Figure 2.8a. This finding can be explained by a high variance: separate analyses for each input modality revealed that input modalities which include no or only slight deformation of the skin, i.e. multi-touch, grab, and press, were perceived as easy to perform on the palm. In contrast, input modalities that involve strong deformation, as twisting and pulling, were perceived as particularly hard to perform.

Elbow and upper arm received the lowest scores for perceived comfort. Participants mentioned that the elbow was hard to reach and that they perceive interaction on the elbow to be socially uncomfortable: “I would not like to interact with anything on my elbow” [P19].

2.3.7 Meaning of Locations

Ordered Arrangements. For all three ordering criteria (frequency of use, importance, and liking) we found two mutually contradicting concepts: The majority of participants (see Table 2.1) placed frequently used and most important/liked items close to the hand. Their reasoning was to have them ready-at-hand. Items extended in decreasing order towards the elbow and the upper arm. In contrast, a minority of participants (9% for frequency, 18% for importance, and 15% for liking) chose the reverse order: most frequently used, most important, or most liked items were placed close to the body. The arrangement extended from the upper arm towards the hand. These participants wanted the highest-ranked items “to be near to me” [P18], “close to my heart” [P14], or to give them a “kind of protection” [P16] by placing them close to their body.

Private vs. Public. In T3 we asked participants where they would like to interact with private and public information. For private, all participants preferred the inner side of their upper limb, which is not easily visible to others. The outer side was mainly used for public interactions. 41% of participants preferred specifically the palm for private interactions, because it can be closed: “We used to write on the palm for cheating in an

Input	Preferred Locations
Handwriting	Palm (59%)
Keyboard	Forearm (82%)
Numpad	Palm (45%)
Sketching	Palm (41%)
	Forearm (41%)
Touchpad	Palm (45%)
	Back of the hand (36%)

Table 2.2: Non-gestural input of T3 and their most preferred locations

exam. It's possible to hide things there" [P2]. This finding lends empirical support to prior research on visibility on forearm-worn displays [161].

Positive vs. Negative. The palm tended to be associated with positive actions, while the back of the hand was associated with negative actions. "For me, the palm is more positive" [P17]. The gesture for 'accept call' was performed more than twice as often on the palm (36% of participants) than on the back of the hand (14%). In contrast, 'reject call' was preferably mapped to the back of the hand (32% vs. 14% on the palm). Also the thumb was associated with positive actions (Accept Call; 18% of participants) due to the common 'thumbs up'-gesture. In contrast, the pinky was associated with negative actions, since it is farthest away from the thumb.

Temporary vs. Permanent. Some referents of Task 1 contained variations that differentiate between temporary and permanent actions, e.g. closing temporarily vs. permanently. These variations were expressed by 27% of participants using different directions: Movement on the upper limb towards the body, i.e. towards the shoulder, was associated with temporary actions ("move it somewhere to the back" [P21]). This confirms prior design on forearm-worn displays, which uses movement towards the sleeve to store information for later usage [161]. The same participants associated movement away from the body, i.e. towards the fingers, with permanent actions ("moving something away" [P21]). This is similar to dragging the element off-screen as found in prior user-centric tabletop studies [243], but accounts for the different input location.

2.3.8 Design Implications

Based on the above findings, we derive the following implications for on-skin input. They provide guidance for the device classes and interaction techniques of this thesis (Chapter 4, 5, and 6). Furthermore, they can guide developers and interface designers of future on-skin sensors.

Gestures and Input Modalities

Results of the study show that participants intuitively made use of the added possibilities provided by on-skin input. Skin-specific gestures, which involved more input modalities than multi-touch alone, were frequently used for distinguishing between variations of a command as well as for performing emotional or interpersonal commands. By leveraging physical affordances specific to skin and by taking inspiration from the way we interact with other people using touch, users could perform more expressive gestures to better convey the command. In particular if an interface comprises functionality that relates to interpersonal or emotional dimensions, it should provide support for gestures that go beyond multi-touch. Irreversible commands can be mapped to uncomfortable modalities (pulling and twisting), in order to prevent accidental input. Social acceptance needs to be taken into account; in particular scratching needs to be considered with care.

Furthermore, results of the study show that users transfer established multi-touch gestures from conventional touch displays to on-skin input. Therefore, on-skin interfaces should support multi-touch input for established standard commands.

We contribute a first user-defined set of skin-specific gestures. It comprises a set of skin-specific gestures for standard commands and variations (Figure 2.7a+c). These gestures increase the input space with expressive gestures, reducing the need for menus or explicit interface elements, which might take up valuable screen space. For instance in a picture gallery touching can be used for selection, while scratching deletes the picture. Skin-specific modalities also allow for fast access to critical commands, e.g. an emergency signal, by avoiding complex multi-touch gestures and reducing the false-positives of touch input. In addition, we contribute a conflict-free set of gestures for emotional expression (Figure 2.7b). Deployed in mobile computing, such gestures could support a more personal way of input for remote communication. They could also enable novel ways of interacting with computer contents. For instance, user interfaces could offer emotional skin gestures for commands that imply some emotional semantics, e.g. liking and disliking photos or Web pages, or prioritizing contents.

Location of Input

As a general rule of thumb, the non-dominant forearm is the location to consider first when designing for on-skin input on the upper limb. 50.0% of all gestures were performed on the non-dominant forearm. Moreover, the forearm has the highest values of perceived ease and comfort.

However, 19% of gestures were performed on the back of the hand and 18% on the palm. The palm was especially preferred for private interaction and for interaction that requires a high degree of precision. Precise interaction took benefit from the accurate tactile feedback in the palm. Applications that require high precision input, such as sketching and handwriting, would benefit from a biologically inspired sensor that provides a higher sensing resolution at this location.

On-Skin Sensors

Prior work has contributed non-invasive optical techniques for sensing multi-touch gestures on skin [61, 68]. In contrast, we are not aware of any existing sensor that would allow for capturing the skin-specific gesture set that was identified above (see Figure 2.7).

The two most frequently used skin-specific input modalities were press and grab. In consequence, a very large subset of gestures could be sensed by combining multi-touch sensing with a pressure sensor. This accounts for 87.5% of all skin-specific gestures performed in the study and for 19 out of the 23 gestures of the consolidated set.

Three gestures comprise shearing, squeezing, and twisting. This requires detecting lateral forces. These could be captured by a shear sensor presented in [154] or by a depth camera that performs a highly detailed capture of the deformed skin's surface topology. One gesture involves shaking, which could be detected using an accelerometer.

Complementary Devices for Output

In our study setup, we have deliberately opted against providing any system output, to avoid biasing participants by a specific form or a specific location of output. In the following, we discuss implications from our findings for several promising classes of devices that can complement on-skin input by providing output to the user.

Off-skin output. All gestures we have identified can be performed in an eyes-free manner, due to proprioception and tactile feedback. Hence, our results inform most directly those application cases in which skin is used for input only, while a complementary device provides visual, auditory or haptic off-skin output. This comprises controlling a distant mobile device, which is carried on the body or in a pocket and provides auditory, or haptic output (e.g. smart phone, music player, and imaginary interface [58, 59]). This also comprises controlling a head-mounted display or an external display that provide visual output (e.g. public display or TV [34]).

Handheld mobile devices. For handheld devices with a touch display, such as mobile phones or tablets, the lower arm, hand and fingers can provide complementary input space. This can be used for more expressive or more personal ways of input than possible on the touch display.

Smartwatches. Our results show that on-skin input is most compatible with smartwatches for several reasons. First, similar or even the same multi-touch gestures than on touch displays are intuitively performed on skin, while skin-specific modalities add more expressiveness of input. Second, our results show that the forearm and the hand are most preferred locations for on-skin input; both areas are in direct vicinity of a smartwatch. However, it can be assumed that some location preferences would differ from our findings, given the fact that output is provided right on the body and within the input area.

On-skin projection was proposed in prior work as a compelling form of output on the forearm and on the hand [61, 68, 69]. Our findings provide additional empirical support for the locations chosen in this previous work. Since in this scenario input is fully co-located with output, those input modalities that strongly deform the skin might interfere with output, as they distort the projection surface. It can be expected that this decreases their perceived ease and comfort. Furthermore, we expect some gestures might change when users perform them directly on visual output. We believe this is particularly likely for the gestures expressing anger (see Figure 2.7b). These might be perceived as being too aggressive if they are performed on a photo or live video of another person.

2.3.9 Limitations

The study was conducted indoors during summertime. Most participants were short-sleeved or could easily uncover the skin of their upper limb. No participant mentioned clothing as an issue during the study. Clothes might lower the accessibility of some locations or make them inaccessible, e.g. in cold weather conditions. In these cases, on-skin input is restricted to the uncovered areas while cloth replaces skin as interaction surface [97] on the covered areas.

Participants were seated during the study. While this allowed for elicitation of mental models in a comfortable setting, gestures and locations might vary in other conditions, e.g. while standing or running. This should be investigated in future work.

2.4 Conclusion

This chapter contributed a background on skin, showing that it is a complex organ with various functionalities and receptors. This creates many opportunities and challenges for on-skin input sensing, which were not covered with traditional multi-touch input. The chapter also details on the findings from an elicitation study about on-skin input. The findings show that users have unique mental models when interacting on skin. They use the variety of body locations for interaction and expressive input modalities. These two principles will be investigated in the following chapters of this thesis.

Various Locations. Skin is the largest human organ and offers many locations for interaction. Different locations can be used to spatially distribute user interface elements to allow for a larger input surface. Half of all user-defined gestures observed in the study were located on the forearm, showing that the forearm a very well suited location for on-skin input. The palm should be considered for precise or private interactions. This empirically confirms prior designs that focused on the forearm and palm [34, 58, 59, 61, 68, 69, 122, 154, 161].

The findings also show that the variety of body locations is important, since people have different mental models and prefer to distribute interactive elements on their bodies. Some locations provide semantic associations for different interaction types. For example, the inner and outer side of the arm can provide different privacy levels. Moreover, the use of different body locations can ease the recall of UI elements [9]. In addition, the body is highly curved with many small peaks and valleys, e.g. on the knuckles. These *challenging geometries* provide visual and haptic cues, but are challenging for on-skin technologies. On-skin interfaces should support accurate and robust sensing on a wide variety of challenging body geometries.

Expressive Input Modalities. On-skin interaction allows for traditional multi-touch input and novel skin-specific input modalities, e.g. pressure, grabbing, and squeezing. Participants intuitively performed skin-specific gestures: they leveraged the physical affordances of skin and took inspiration from interpersonal touch. This allowed them to better express emotions, variations of commands, as well as standard commands, which relate to interpersonal communication. For many standard commands, conventional multi-touch gestures were successfully transferred from touch-input devices to skin. Overall this demonstrates the wide spectrum of skin as an input surface, which is highly compatible with existing forms of multi-touch input, but in addition enables substantially novel forms of skin-specific input. These include uncomfortable gestures that were explicitly desired for some types of commands. Participants performed physically uncomfortable gestures for irreversible actions, to avoid accidental input, and for expressing negative emotions. Taken together, these expressive input modalities have the potential to create more expressive interactions for mobile computing.

The next section will discuss the state-of-the-art in wearable interactions. Further, we will detail on existing approaches for on-skin interaction with respect to two main themes identified above: various input locations and expressive input modalities.

3 | State of the Art

The research of this thesis was inspired by related work of three major fields (see Figure 3.1): human skin, interaction with wearable devices, and soft and thin-film electronics. The previous chapter gave a background on the structure and properties of *human skin* and prior empirical studies in the field of on-skin interactions. Based on this knowledge, we will discuss the state-of-the-art of wearable devices, on-skin technologies, and soft and thin-film electronics. Foremost, this thesis is informed and inspired by prior *interactions with wearable devices*. This chapter starts by giving an overview of prior interaction techniques on and around rigid wearable devices. Based on this knowledge, section 3.2 will elaborate *on-skin interactions* using different input and output technologies. Finally, the last section discusses advances in *soft and thin-film electronics*. These inspired the fabrication of the novel on-skin devices presented in this thesis. Where appropriate, we will discuss similarities, differences and the novelty of this thesis.

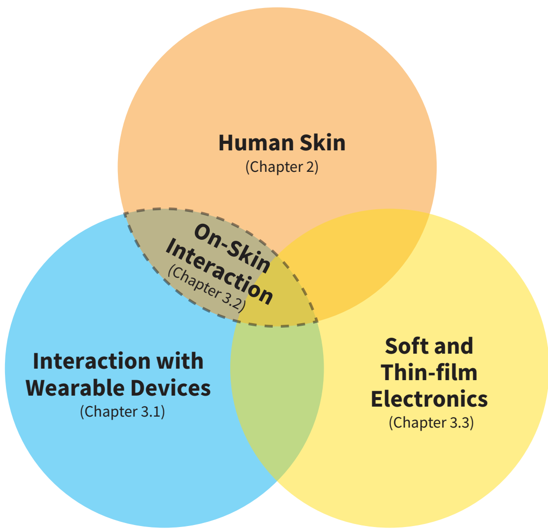

Figure 3.1: Related fields of this thesis

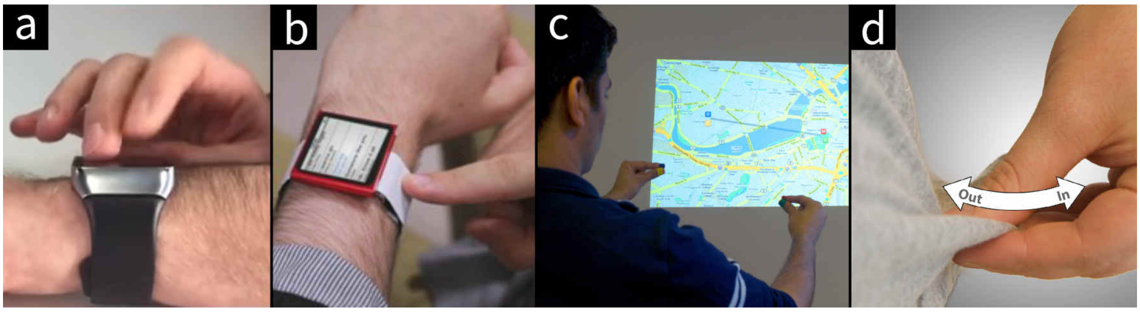

Figure 3.2: Interactions with wearable devices: (a) expressive tapping on a rigid smartwatch display [152], (b) sliding on the wristband [166], (c) interaction on the walls [145], and (d) interaction on clothing [97].

3.1 Interaction with Wearable Devices

Wearable devices have been researched for a long time. Early wearable devices include the timing device to predict roulette by Thorp and Shannons in 1966 [216] and the calculator watch by Hewlett-Packard in 1977 [136]. In 1981, Steve Mann built the a general-purpose wearable computer including a backpack-mounted computer, head-mounted display, and chorded keyboard [135]. However, it took recently advances in consumer hardware to make commercialization of wearable computers possible. The key enabler were the miniaturization of sensor technologies, increases in solid state storage, advances in low-power processors, wireless communication, and interface technology [187].

This section discusses prior work on wearable interactions: input on small rigid devices, around those devices, and contact-less input techniques.

3.1.1 Improving Input on Small Devices

Wearable devices, e.g. smartwatches and head-mounted displays, trade-in the size of their input surface for wearability. This is problematic for touch input, because targets become too small to touch and the finger occludes most of a touchscreen. Wang and Ren [227] recommend touch targets of at least 11.5 mm. This limits the amount of interactive elements on these devices. For example, an average smartwatch with a display diagonal of 1.3" to 1.6" allows only for 4–6 touch targets.

Prior work addressed this problem by proposing novel interface elements, e.g. novel keyboards to improve typing on small surfaces [52, 81, 197]. These keyboards are designed for the small display of a smartwatch [81, 197] and the small touch surface of head-mounted displays [52]. As a hardware solution, Xia et al. [245] proposed a finger-worn nano-stylus to increase the effective touch resolution on the display.

Beyond commercial devices, finger-worn wearable devices are an active research stream with small input surfaces [199]. These nail-worn displays [211], touch surfaces [95], and touch-sensitive rings [21] are fast to access and allow for single-handed input. Despite their small size, they allow for basic touch gestures that are fast to perform. However, similar to other small wearable devices, they have a limited input vocabulary due to their small surface.

As an alternative approach, prior research investigated expressive interactions that do not only take the touch location into account. Oakley et al. [152] suggest tapping gestures on a small display (Figure 3.2a). They propose two-finger tapping for smartwatches, which take the spatial and temporal dimension of touch contacts into account. Ashbrook et al. [4] propose subtle and eyes-free input with a magnetically tracked ring. Xiao et al. [246] presented pan, twist, and click input for smartwatches.

Also expressive interaction techniques intended for handheld devices can potentially be used on wearables. These include sequential tap events [182], roll and slide events of the finger [183], and contact size-based interactions [12]. Moreover, wearables can also include other input modalities presented for mobile devices, e.g. two-dimensional trackpoint gestures [242].

Beyond single-device interaction, Duet [23] increases expressiveness of interaction through joint interactions with a smartwatch and a smartphone. These joint and cross-device interactions allow for a rich set of applications and interactions [26, 53, 82]. Although these interaction techniques are intended for touchscreen devices, they show benefits and possibilities to expand the input vocabulary of touch interactions.

In addition to input, prior research also investigates small output devices. Harrison et al. [63] investigated the expressiveness of point lights. Roumen et al. [184] studied different output modalities for the small form factor of a ring. Considering the public visibility of body-worn displays, prior research investigated using these small displays as public displays [161, 165].

3.1.2 Enlarging the Interactive Surface

Another approach to improve interaction on wearable devices is to increase the size of their interactive surface. Prior work leverages previously unused parts of wearable devices as an input surface. This includes touch-sensitive wristbands [166] (Figure 3.2b), bezels [151], the back of a head-mounted display [55], and cords [190, 191]. Others proposed adding multiple connected rigid components to increase the interaction space [134, 161]. Such interactive components do not have to be stationary, but could move around as on-body robots [30].

Although these prototypes increase the input space, their interaction space is still limited by the rigid nature of the device. The next sections describe interaction spaces close to wearable devices. They can be used to extend input and output capabilities beyond the rigid form factors.

3.1.3 Passive Surfaces in the Surrounding

Instead of touching body-worn components, this research stream investigates wearable systems that allow for interaction on passive objects, e.g. walls, tables, or books. Despite having a small, wearable form-factor, these devices allow for interaction on larger surfaces. When touched, the objects provide tactile feedback to the user.

WUW [145] and OmniTouch [61] are both wearable systems worn on the head or shoulder. They allow for interaction on passive surfaces in the environment (Figure 3.2c). Both use a body-worn pico-projector to augment the objects with visual output. An optical sensor, e.g. a rgb camera [145] or a depth-camera [61], detects the hand for input. The user interacts by touching the surface [61, 145] and by performing multi-touch gestures [61]. Noteworthy, the environment does not need any augmentation, because all input sensors and output devices are worn on the body. Hence, the body worn components can be small, but the interaction can use a larger surface on-demand.

Researchers investigated finger-worn wearable devices that sense touch contact with passive objects. MIDS [112] is a finger-worn devices to detect finger movements and taps on a table. It uses accelerometers worn on the middle segment of the finger to replace computer mice and keyboards. Similar, FingerSight [101] allows for 2D tracking on any surface, but can be worn on the finger-base. Yang et al. [248] presented a thimble-like device that detects the texture of a touched object. It allows for tap and gestural interactions on everyday objects. Mascaro et al. [137] proposed a finger-nail worn sensor to detect the applied force. The sensor measures color changes on the nail and detects normal and shear forces on any object. Hsiu et al. [83] measured tap and swipe gestures by augmenting the nail with a grid of strain gauges. Without touching the object, EyeRing [148] and FingerReader [198] allows for interaction with the environment through pointing. A finger-worn camera detects objects and printed text to assist visually impaired users and to enable novel pointing interactions.

The interactions require access to additional input surfaces. However, such surfaces are not always available in mobile scenarios, e.g. during sport, or might temporarily bind the user to a specific location, e.g. a wall or a table.

3.1.4 Clothing and Accessories

Clothing has also been researched as an interactive surface [16, 25, 97] (Figure 3.2d). Recent advances in conductive yarns allow for weaving of touch-sensitive electrodes into textiles at large scale [170]. Interactive clothing allows for capacitive [79] and resistive touch sensing, pressure sensing [71, 255], strain sensing [250], and activity tracking [24]. Textiles on the finger can allow for multi-modal sensing by combining pressure and bend input [250]. Randell et al. [173] used smart textiles in a jacket to communicate with a remote partner through affective gestures. Schneegass et al. [189] investigated stroke based gestures and taps on smart sleeve. In proCover [119], Leong et al. augmented a prosthetic limb with a pressure sensor for tactile sensation and feedback. Devendorf et al. [32] investigate the use of thermo-chromic yarns for visual output on textiles. Smart textiles are also sense environmental changes [16], e.g. to detect chemicals and gases or react on temperature and humidity changes. Beyond clothing, Komor et al. [109] studied input on a messenger bag with little to no visual attention. In addition, other body-worn accessories such as belts [36], socks [39], hair extensions [219], and shoe-soles [138] can be used for wearable interactions.

Smart clothing and accessories are very promising fields that share common properties with on-skin interaction. Both, clothing and skin, provide a large, always-available non-rigid input surface for mobile computing. Despite these similarities, there are also major differences: From the interaction perspective, clothing provides different physical and functional affordances than skin. The textile reduces tactile cues depending on the used materials and its overall thickness. Moreover, localization of UI elements is more challenging, because clothes can move on the body. Finally, people might have different mental models and associate different interactions with each surface. Technology-wise smart clothing is mostly based on conductive yarn, which integrates itself into existing fabrication processes, e.g. by supporting existing textile weaving technology and equipment [170]. However, such textile-based approaches are unusable for other surface types like skin. Beyond similarities and differences, there remains a great potential in the integration of both technologies. This could allow for seamless interactions that use the best of both surfaces.

3.1.5 Contact-less Body Gestures

Contact-less interactions are an alternative to touch input on and around the device. They use the position or pose of body parts for gesture input with the mobile device.

Motion input is performed in the surrounding empty space, which forms a large, always-available, three-dimensional space. Early work by Metzger et al. [143] investigated in-air swipe gestures. The user swipes his fingers forward or backwards past an embedded proximity sensor. This allows for simple number entry, e.g. to control a headset. Kim et al. [105] extended this concept enabling multi-directional gesture input above a smartwatch. An array of proximity sensors also allows for rich interaction using wrist gestures [47]. Song et al. [203, 204] investigate in-air gestures using the RGB camera of mobile devices.

Besides optical approaches, magnetic sensing can be used to detect a finger close to the device. Harrison et al. [65] investigated interactions in proximity to a smartwatch. The finger position is sensed using an embedded magnetometer and a passive magnet attached to a fingertip. This allows for rotational input around the device, gestures, and pointer input. uTrack [22] shows 3D position tracking of the thumb using magnetic sensing.

Gustafson et al. [57] investigate imaginary interfaces. These are screenless wearable devices that allow for spatial and gestural interactions. The in-air gestures allow to use a large space around a small device. In contrast to touch interaction on skin, in-air input does not provide tactile feedback to the user. Finally, Soli [120, 229] is another highly accurate motion tracking device based on millimeter-wave radar. Soli does not require augmentation of the hand, but requires the gesture to be performed in front of the sensor, e.g. above a smartwatch.

Similar to prior techniques, retractable controls allow for using the empty space around the devices. Blasko et al. [11] investigated interaction techniques for a retractable string. The string can be pulled from the side of a smartwatch. It provides distance and angular input and adds 1D visual output. Elasticcon [106] is a belt-worn, retractable controller. Although the string confines the input space, the controller enriches the interaction using additional knobs, string manipulations, and haptic feedback.

Arms and hands allow for a rich set of poses and gesture to interact with mobile devices. Starner et al. [208] pioneered wearable gesture based input with the gesture pendant. The gesture pendant is a chest-worn infrared camera to detect hand gestures in front of the device. It supports a large input space despite the small device. Similar, Mistry et al. [145] suggest multi-touch inspired in-air gestures and in-air drawing. ShoeSense [6] moves the camera position to the shoe. This novel perspective allows for three types of hand gestures. The user interacts with the system by forming triangles with the arms, using radial gestures, or through finger-count gestures. These can be performed without visual attention. Armura [68] further investigates the interaction space of hand gestures with and without visual output. It demonstrates interactions using one and two arms, including menuing, crossing gestures, cursor control, and peephole displays. More recent, Cyclops [19] extends the concept to support full-body gestures. It supports input from all limbs, i.e. arm and leg gestures. To sense the larger space in front of the user, it uses a fish-eye lens on a chest-mounted RGB camera.

Data gloves have been investigated for decades [35, 210] to capture the rich dexterity of the human hand for human–computer interactions. These gloves are worn on the complete or parts of the hand to capture input from the hand hand movements and the hand pose [258]. While augmentation of the hand with gloves eases accurate data capturing, wearing a glove might not always be desirable in mobile scenarios. Hence, researchers investigated hand-gesture recognition with glove-less systems. Simple hand poses can be estimated by using unobtrusive wrist-worn sensor bracelets. They can either use capacitive sensing [175], photo reflectors [40], electrical impedance [251, 252], bio-accoustic [2, 33], or pressure sensors [31]. An estimation of the finger angles can be also achieved by tracking the skin motion of the back of the hand [121, 231]. However, these techniques only allow for relatively coarse pose estimations. The hand pose can be detected with finger-worn [18], wrist-worn [102], or body-worn [126] optical sensors. Finally, also surface electromyography (sEMG) allows for sensing hand and finger gesture [3, 185, 186].

Body gestures are not the focus of this thesis, but have the potential to increase the expressivity of on-skin touch input. In chapter 5, we use pose-based input to enable dynamic interface elements. For example, the same touch location can either control the volume on a straight finger or fast forward a song on a bend finger.

3.2 On-Skin Interaction

This section gives an overview on the related work in the field of on-skin interaction. On-skin interaction is an emerging stream of human–computer interaction using the skin as an interactive surface for mobile computing. Prior research proposed interaction techniques, as well as, novel input and output technologies to enable on-skin interfaces.

3.2.1 Interaction Techniques

The skin was proposed for several interaction techniques. Early work investigated *tapping* on the skin [69, 122]. Tapping has been shown to be an accurate input modality on the skin that provides two-dimensional touch positions. It has been used to implement various user interfaces, e.g. for remote-controls [34], imaginary phones [58], keyboards with 26 keys [225], and as additional buttons for smartwatches [113].

Harrison et al. [61] extended the input vocabulary to *multi-touch gestures*, e.g. swiping and pinching. They have been investigated for gesture input on the palm [226], on the cheek [195], and on smaller surfaces like the fingerpad [20].

Wagner et al. [223] combined coarse on-body touch input with mid-air pointing. This allowed for combining body-centric touch input with output that is fixed in the surroundings. They found that the combination of touch and pointing is significantly slower than pointing alone. Hence, interaction designers should consider interaction effects between on-body touch and other simultaneous input techniques.

In contrast to the rich *skin-specific modalities* that have been used during our empirical study (see Chapter 2.3), prior work focused only on the dominant input modality, i.e. multi-touch input. As an exception, Ogata et al. [153, 154] investigated skin as a soft interface for force-based input. Their technical enabler allows for sensing pressure and tangential forces applied on skin. The force-input was suggested to control a cursor for head-mounted displays [154] and for interactions with smartwatches [153]. Chapter 6 builds on these input primitives and investigates novel interaction techniques for wearable computing that use high-resolution and multi-dimensional force input.

3.2.2 On-Skin Sensing

Prior research in human–computer interaction presented several sensing technologies to capture on-skin input (Figure 3.3):

Optical Sensing

The most common approach is optical sensing. Prior work sensed on-skin input using RGB cameras [145, 214] or depth cameras [34, 58, 61, 68, 69]. The camera is either mounted on the shoulder [61, 69, 68], head [145, 214], or for prototyping on an external

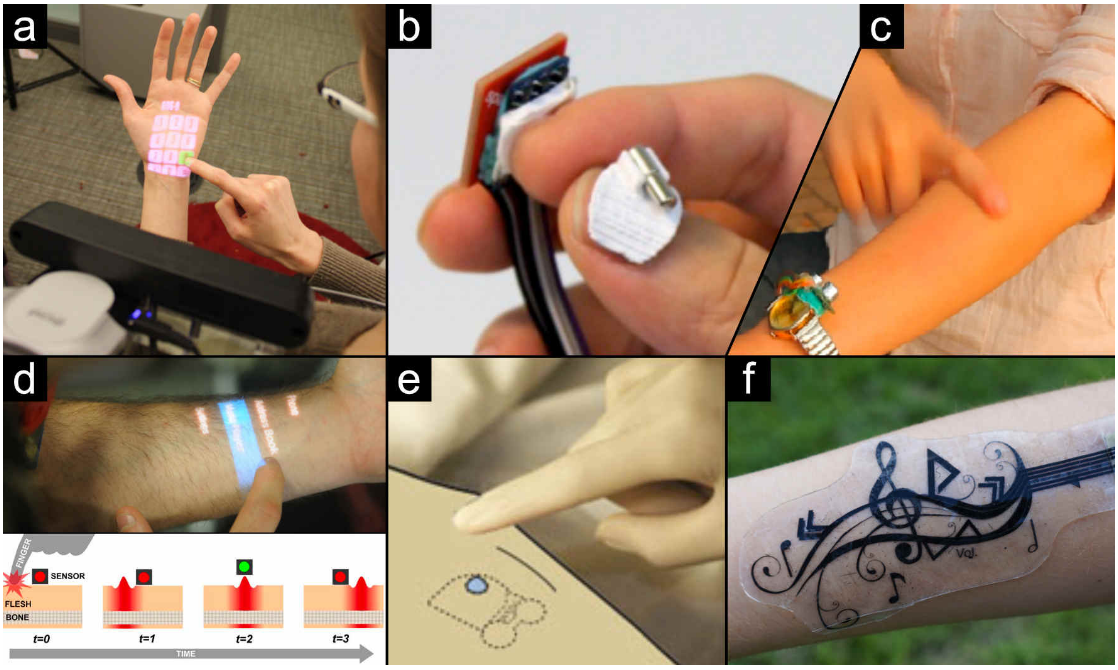

Figure 3.3: Examples of different on-skin sensor technologies: (a) optical sensing using depth cameras [61], (b) magnetic sensing [20], (c) ultrasonic sensing [122], (d) accoustic wave-propagation through the body [69], (e) implants [80], and (f) on-skin devices (Chapter 4 [234]).

tripod behind the person [34, 58]. This allows for interacting directly on the skin, but requires direct line-of-sight to the camera and is susceptible to lighting conditions.

Another approach attaches optical sensors close to the skin. These proximity sensors require less processing power than camera setups. Prior work has used photo-reflective sensors to sense touch input around small devices [14], touch input on the back of the hand [147], and touch input next to a smartwatch [113]. Ni and Baudisch [149] propose a reversed optical mouse sensor to capture input performed by moving a finger on the sensor. The work shows the feasibility of discrete 2D gestures, e.g. marking gestures and unistroke text entry.

Beyond touch, Ogata et al. suggested photo-reflective sensing for measuring skin deformations [153, 154, 155]. Their approach uses one or multiple armbands with infrared reflective sensor arrays pointing towards the skin. The sensors measure the distance to the skin to recognize deformations of skin, e.g. shear and pull input. Mascaro and Asada [137] augment the finger to detect force-input on any surface. They sense the reflection intensity of the skin under the finger to detect the deformation forces. Their artificial fingernail sensor is based on multiple LEDs and photo-diodes. Nail+ [83] extends the concept to detect ten force-tap and swipe gestures.

Magnetic and Electrical Field Sensing

Another approach consists of magnetic sensing, similar to in-air input around smartwatches [65]. It uses magnets and Hall-effect sensor grids attached to the body [20, 85]. Chan et al. [20] present private and subtle gesture input on the fingertip. The Hall-effect sensor is mounted on the nail behind the finger and a magnet is attached to the interacting thumb. Magnetic sensing allows for tapping and gesture input. However, it falls short in detecting precise touch-down and touch-up events. Furthermore, it is an open question if magnetic sensing is able to support other input modalities than touch and if it transfers to geometrically challenging body locations.

Electrical field sensing allows for sensing without augmentation of the interacting finger. Zhou et al. [256] demonstrate its potential for touch and slide input on the skin next to a smartwatch. They use shunt-mode, i.e. emitting and receiving between electrode pairs, to detect when the finger interferes with the electric field. However, as for magnetic sensing, it has only been proposed for areas with low curvature, e.g. the forearm.

Radar and Ultrasonic Sensing

Radar-based sensing [120, 229] use high-frequency, short-range radio-frequency signals. This technology senses motion at a fine level with a high temporal resolution. It enables motion, range, and velocity sensing, which can be used to detect gestures with quick motion, e.g. swiping and shaking. However, the low-spatial resolution makes tracking of spatial configurations, e.g. the touch location, difficult.

Ultrasonic sensors can be attached to the skin surface to detect the interacting finger [122]. The sensor measures the distance to a single, interacting finger to determine the touch location. However, accurate tracking requires a direct line to the finger. The technology does currently not work for multi-touch and on challenging geometries.

Wave-Propagation Through the Body

Another approach investigates the propagation of various signals inside the body. Harrison et al. [69] proposed bio-accoustic sensing for on-skin touch sensing. Firm touch input creates vibrations that are reflected and propagated inside the body. The signal can be measured with an array of sensors to localize the touch contact. Matthies et al. [139] measure the unique electrical signature of different body parts with capacitive and EMG sensing. This method supports contact-based input on various body locations, including detection of soft and long touches. Both approaches work on many body locations and do not require a sensor overlay. However, they currently have a low spatial sensing resolution and allow for single-touch-only sensing.

The propagated signal does not have to occur natural during a touch. Active signal propagation can be used for personal area networks [77, 257] and to transmit audio signals [41, 42]. It also can be used to track touch input. Muhibiya et al. [146] showed that touch and pressure on the skin can be detected by creating ultrasound signals. They are propagated on the skin and can be measured using a finger-worn receiver. Zhang et al. [253] presented a similar principle using electrical signals. A ring emits a high frequency AC signal that is sensed using a wristband. The phase delay between the electrodes allow for touch detection with a mean error of 7.6mm. Both approaches do not require a direct augmentation of the interaction surface. Compared to camera solutions, they do not suffer from occlusion problems. However, they require two skin-worn electronic components, i.e. an emitter and a receiver.

Implants

Implants allow for electronic components under the skin. In addition to medical applications, they have been used for identification through RFID, to implant passive magnets, and to permanently augment senses with technology [232]. Holz et al. [80] investigated implanted user interfaces for on-skin interactions. These could support touch, hover, LEDs, vibrations, audio input and output. Another interesting permanent approach is tattooing functional inks [10]. Such technologies require surgery and intrusive modification of the body. In contrast, the devices proposed in this thesis are all temporarily attached on the skin and are easy to attach and detach by the user.

On-Skin Devices

A final class of contact-based input are on-skin devices. On-skin devices allow for touch-sensitive interfaces directly on the skin. The skin-worn electronics are thin, flexible, and stretchable, similar to band-aids and temporary tattoos. They are inspired by research on electronic skins for robots and prosthesis as well as epidermal electronics that sense medical information on the body (see Chapter 3.3). Recent advances made skin electronics thin, bio-compatible, and robust enough to be worn on the skin for on-skin interaction.

The advantages of this technology for on-skin interactions is the close proximity to the surface. Touch input is performed directly on the electronics. This allows for precise touch localization, approximation of the contact area, and detection of touch-down and touch-up events. It also has the ability to sense force and deformation input, e.g. pressure, shear, squeeze and bending. Furthermore, on-skin devices can be customized for sensing on various body locations.

These properties make on-skin devices the ideal sensing technology to investigate the two main principles for on-skin interaction derived in section 2.4: various locations and expressive input modalities. Hence, this thesis proposes novel form factors and on-skin interfaces based on skin electronics. Chapter 4 investigates stretchable sensors for touch and pressure input on the skin. These sensors can be wrapped around the body, attached to wearable devices, or attached to the body using biocompatible adhesive. Chapter 5 further extends this concept showing conformal input and output sensors on temporary tattoos. It is able to sense touch contact, squeeze input, and bending of body parts. It also provides visual output using electroluminiscent displays.

Although on-skin electronics are an emerging field in human–computer interaction, other research groups independently investigated similar solutions. Vega and Fuks [221] proposed conductive ink for interactive make-up, e.g. eyeliners. In parallel to our research, Lo et al. [127] presented thin interactive temporary tattoos with touch and bend sensing, as well as, small, rigid pointlights. Similar, Kao et al. [96] proposed a rapid fabrication for visual aesthetic on-skin interfaces. Wessely et al. [238] demonstrated the fabrication of stretchable, touch-sensitive EL displays that can be worn on the body.

3.2.3 On-Skin Output

The primary contributions of this thesis center around input on the body. However, in addition to input, we contribute interactive tattoos with co-located visual output in chapter 5. The output is inspired by prior work on haptic and visual output on the skin. This allows for fast feedback and private notifications in mobile scenarios.

Haptic Output

The mechanoreceptors inside the skin can be stimulated by wearable devices for haptic output. The stimulation can be created with vibrating motors [117, 184], piezoelectric actuators [164], poking solenoids [184], and by dragging a physical tractor across the skin [86]. The skin can also be stimulated by changing the temperature of a wearable device [184, 240] or by creating airflow towards the skin [116]. Moreover, skin-worn electrodes can stimulate nerves and muscles through electrical stimulation [129, 247].

Visual Output

Visual output can be either projected on the skin or overlayed with on-skin displays:

Body-worn projectors allow for projection of visual information, e.g. UI controls, directly on the skin. The projector can be worn on the head [145] or shoulder [65] to project on the forearms and hands. The body is tracked with an additional camera. Projection mapping can correct the perspective and remove jitter to allow for stable projections. Besides displaying UI elements, on-skin projections allow for skin games [15] and can be used for light therapy [171].

Another approach visualizes information with skin-worn displays. Rigid OLED displays have been attached to the rigid surface of the fingernail [211]. Displays worn directly on the skin require flexible and stretchable displays. Burstynet al. [13] propose an e-ink display attached to the wrist. Lo et al. [127] attached LEDs to thin temporary tattoos. These tattoos highly conform to the body, but the pointlights have limited output capabilities. Kao et al. [96] proposed thermochromic displays. They allow for custom-shaped displays, but have have a slow response time. In comparison, electroluminiscent (EL) displays have a very fast response time. Wessely et al. [238] embedded EL displays in stretchable silicone and proposed them for custom-shaped on-body output. Inspired by this work, we investigate very thin and conformal EL output on thin tattoos. They enable on-skin interaction researchers to prototype their own custom-shaped and very thin on-skin displays that can be used on challenging body locations (see Chapter 5).

Noteworthy, the output techniques of prior work can be combined with the on-skin devices of this thesis for integrated input and output. Besides output directly on the skin, our proposed interaction surfaces can use haptic, visual, and audio output of existing mobile devices, e.g. smartphones, smartwatches, head-mounted displays, and headphones.

Taken together, on-skin interaction is a promising field for wearable computing. Prior research proposed first basic interaction concepts and implemented them with novel sensor technologies. The interactions were primarily based on traditional multi-touch input for rigid mobile devices, e.g. tapping, sliding, and gesturing. The sensor technologies have enabled interactions on slightly curved body geometries. In this thesis we propose novel skin-worn devices that expand the on-skin interaction space. They enable input modalities and locations that were elicitated in our study (Chapter 2.3). Hence, they advance on-skin interaction by supporting multi-touch and skin-specific modalities, as well as, challenging body locations.

3.3 Soft and Thin-Film Electronics

Current on-skin technologies fall short to capture precise and expressive contact-based interactions on various body locations. This thesis present three novel interaction devices, based on soft and thin-film electronics. The following sections will describe related work in the fields of flexible sensors in human–computer interaction, electronic skin and epidermal electronics, as well as soft deformation sensors.

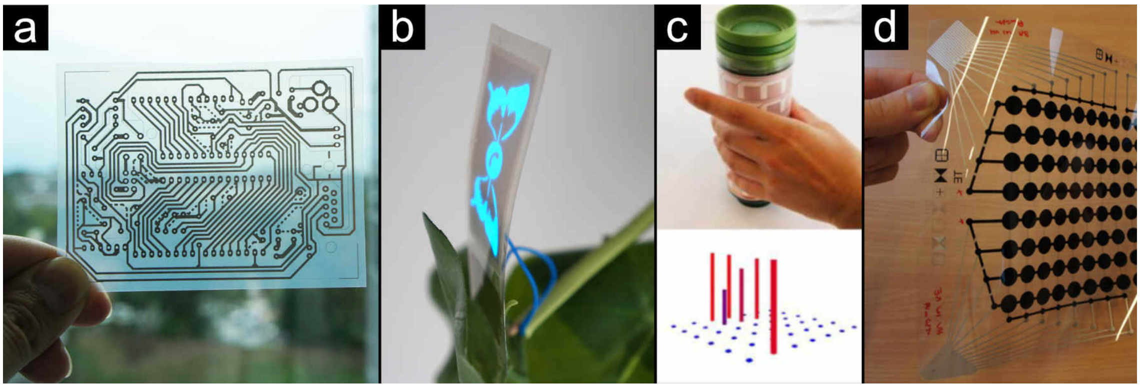

Figure 3.4: Examples of flexible thin-film electronics: (a) ink-jet printed circuit [98], (b) thin and flexible EL displays [160], (c) touch sensor wrapped around a curved object [48], and (d) piezoelectric foil for pressure input [177].

3.3.1 Thin and Flexible Interactive Surfaces

Thin and flexible devices are an on-going research stream in human–computer interaction. These devices allow for paper-like interactions for desktop, tangible, and mobile computing. For example, foldable [43, 99], rollable [100], and highly deformable [209] input devices and displays.

Commercial e-ink displays allow for flexible deformations, e.g. bend sensing [111], and actuations [46]. Rendl et al. investigated piezoelectric foils for pressure-sensitive touch input [177] and sensing of surface deformations [178]. These interaction modalities can be combined to allow for rich physical interaction using touch and deformations, e.g. on the flexible cover of a phone [179].

Advances in printed electronics allow for embedded sensing and output capabilities inside the flexible surfaces. Kawahara et al. [98] propose conductive ink-jet printing of flexible electronics, e.g. to enable touch and bend input [48]. Olberding et al. [160] use screen printing as a DIY fabrication method. Screen printing supports various inks and multi-layer electronics, e.g. to fabricate custom-shaped electroluminescent displays. Both printing technologies support rapid prototyping and are based on a digital fabrication process. The digital designs allow for *personalized and customized electronics*. For example, to support aesthetic circuits [128], folded geometries [159], and custom shapes, e.g. through cutting [158].

Thin and flexbile surfaces can be used for various objects in HCI. The body, however, is non-developable and skin a soft and deformable surface. Hence, on-skin electronics should also be soft and stretchable to conform to the body. Fabrication of such electronics is a complex endeavor that cannot be achieved with prior fabrication approaches in HCI. Therefore, the fabrication methods used for the prototypes in this thesis are based on advances in material sciences and robotics.

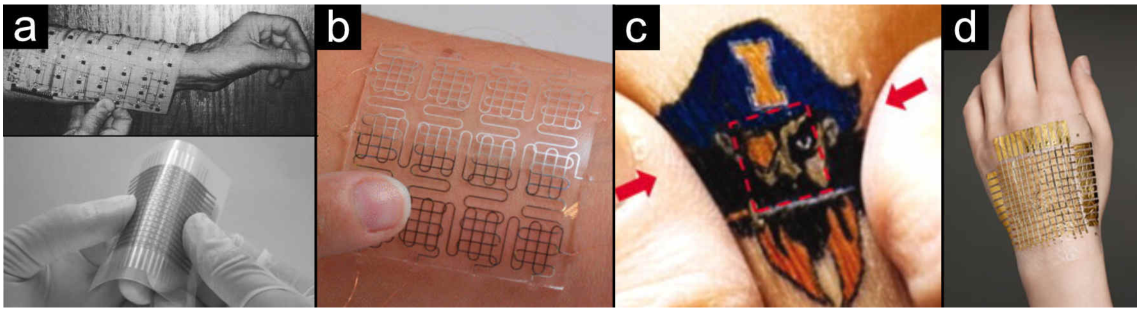

Figure 3.5: Early investigations of electronic skin: (a) pioneering work by Lumelsky et al. [133] (top) and Someya et al. [202] (bottom), (b) a wearable keyboard, proposed by Kramer et al. [110], (c) epidermal electronics [103] for biosensing, and (d) a tactile sensor grid on the back of the hand [201].

3.3.2 Electronic Skin and Epidermal Electronics

Electronic skin (e-skin) are thin, flexible, and stretchable sensors (Figure 3.5). E-skin makes the "effort to create an artificial skin with human-like sensory capabilities" [60]. Research in this area started with the pioneering work of Lumelsky et al. [133] and Someya et al. [202] (Figure 3.5a). The primary focus of e-skin research is to provide multi-modal sensor skins for robots to improve their sense of the environment; soft prostheses that are capable of sensing contact, pressure, or temperature for disabled people; and health-monitoring devices [241]. Beyond input, prior work presented visual output using light-emitting diode displays [193, 224] and stretchable PLED [222, 239]. This work makes electronic skins highly promising for on-skin interfaces. However, many current approaches require specialized lab equipment and are currently unsuitable for rapid prototyping.

Stretchable electronics can be fabricated in two ways [181]. The first approach uses *structural layouts* to make electronics stretchable [228]. For example, Gray et al. presented stretchable electronics with a high conductivity using spring-shaped metal wires [50]. The second approach uses *new materials* in conventional layouts. For example, by using carbon- and silver-doped PDMS [150], PEDOT:PSS [123], and carbon-nanotubes [124]; all intrinsically stretchable, conductive materials. Both, structural layouts and stretchable materials, can be combined to achieve a higher stretchability. The devices presented in this thesis use both approaches. Chapter 4 uses intrinsically stretchable carbon-doped PDMS for touch sensing. Chapter 5 uses PEDOT:PSS and the additional horseshoe-pattern [78] improves the stretchability on body locations with high strain.

In the materials science community, first proofs of concept have shown the technical feasibility of sensor overlays for touch sensing on the body [110, 132, 244]. Kramer et al. [110] presented a pressure sensitive skin overlay composed of PDMS embedded with microfluidic channels of eutectic gallium-indium (EGaIn) alloy (Figure 3.5b). Stretchable electronics are not only able to sense contact pressure, but can also be used as skin-mountable strain gauges for bend sensing [131]. Woo et al. [244] demonstrated pressure and strain measurements using a compressible layer of EcoFlex. While the force measurement is continuous, the sensor is unable to differentiate between pressure and strain. Furthermore, this approach relies on microcontact printing and cleanroom fabrication. It therefore limits possibilities for rapid customization.

Recent advances allow for rapid prototyping of stretchable electronics. Lu et al. [132] use laser patterning of stretchable PDMS and carbon-doped PDMS for rapid prototyping of soft-matter sensors and circuits. The materials are non-toxic and biocompatible. Hence, they are well usable for on-skin electronics. However, their designs are based on exposed electrodes to detect skin contact. This decreases the reliability because skin conductance heavily varies between users and electrodes might become stained or worn through skin contact, increasing resistivity over time. Chapter 4 uses the same fabrication approach and materials to create sensors that are encapsulated inside PDMS. Therefore, increasing the accuracy of touch sensing on the body.

Related to electronic skin, there is an emerging research stream of epidermal electronics [103]. Epidermal electronics are very thin (<50 µm), stretchable electronics worn on the skin (see Figure 3.5c). Their slim structure can allow for robust attachment to skin via van der Waals forces. Hence, it does not require mechanical fixation or adhesive. The slim epidermal electronics also improve conformality to skin, compared with thicker overlays. SEM scans show that membranes of 36 µm conform to larger skin wrinkles and membrane of 5 µm thickness have excellent conformality [90].

Epidermal electronics have been suggested for medical purposes, e.g. to sense temperature [103], sweat [84], and the electrical activity inside the body [89, 103]. They also can be used for interaction purposes: They are able to sense sEMG signals [90], e.g. to detect wrist and neck movements and the bending of a finger. For communication with external devices, they can support near-field communication (NFC) [104].

3.3.3 Soft Deformation Sensors

Soft deformation sensors are another important research stream for this thesis. These sensors allow to increase the input expressivity by sensing deformations, e.g. pressure, shear, and squeeze input. Such soft and skin-like sensors can be embedded into on-skin devices to allow for multi-dimensional deformation input, as it will be discussed in chapter 6.

Many technologies have been proposed for deformation sensing, including resistive, magnetic, and optical sensing. Resistive sensing embeds conductive material inside a deformable object. For example, Vanderloock et al. [218] suggested to fill soft objects with conductive material to measure the resistance across multiple electrodes (Figure 3.6a). Slyper et al. [200] sense deformation of objects through contacts of conductive parts on their outside (Figure 3.6b). FlexiBend [27] is a shape-changing strip made from strain gauges that can be embedded into objects for deformation sensing. DefSense [5] embeds piezoresistive wires into flexible 3D prints. Deformation sensing using magnetic sensing has been presented for deformable silicone [88] and for rigid objects with joints [45, 87].

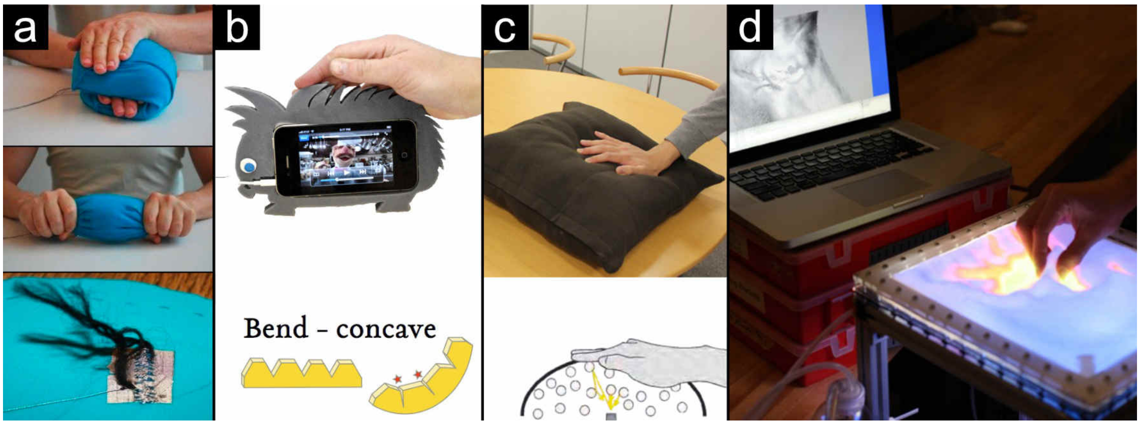

Figure 3.6: Deformation sensing on soft objects with (a) resistive sensing through conductive filling [218], (b) integrated open switches [200], (c) integrated optical sensors [212], and (d) structured light [38].

In the robotics community, optical force-sensitive deformation are used for their fast response and high resolution. Kadowaki et al. [94] measure the light distribution between infrared LEDs and photoresistors in a soft urethane foam. Sugiura et al. [212] measures the reflective IR light inside a deformable object (Figure 3.6c), e.g. cushions and plush toys. Zhao et al. [254] investigate stretchable optical waveguides for soft prosthetic hands. Our prototypes in chapter 6 are based on an optical deformation sensing technique introduced by Tar et al. [215]. Its small form factor ($\oslash 10mm$) and robustness makes it a suitable technology for wearable computing. However, future wearable devices could be based on other technologies, since the proposed interaction techniques are not limited to a concrete sensing approach.

Beyond the scope of this thesis, future soft deformation sensors could change their stiffness for subtle haptic output. Such material changes can be achieved through pneumatic jamming [38, 66, 162, 249] (Figure 3.6d), ferromagnetic fluids [107], and temperature controlled embedded state changes [51, 144].

Energy Harvesting

Although this thesis does not address energy, it is an important limiting factor for wearable devices. The form-factor for wearable devices tends to be too small to carry large batteries. Besides increasing the battery capacity and optimizing power consumption, energy harvesting could become a key enabler for wearable devices. It could remove or at least reduce the need to take off the wearable device for recharging [187].

Energy harvesting uses already available energy sources in the environment or the human body. Prior research investigated various ways for energy harvesting of different sources. One possibility is to harvest solar energy [174] or to harvest the temperature gradient at the body [130]. Wearable devices can also be human-powered [207]. Body movements can be used as an energy source using piezoelectric materials. For example, embedded in the shoe sole, they allow for harvesting energy from walking [196].

Energy can be wirelessly transmitted from one device to another using inductive wireless power transmission [140]. This can allow for transferring energy from a mobile device inside a pocket or for recharging wearables through smart furniture.

3.4 Discussion and Conclusions

This chapter gave an overview of prior research in mobile computing. The research aims to increase input space and expressivity of wearable devices. Compared to other surfaces, skin provides a large, always-available surface. Mobile interactions can benefit from the human sense of proprioception and tactile feedback. Recognizing this potential, prior research proposed various technologies for on-skin sensing.

As concluded in section 2.4, on-skin interaction can benefit from interaction on various locations and expressive input modalities. Most technologies fall short in these two domains, because on-skin sensing is challenging. The disconnect between sensors and skin make accurate touch sensing a complex endeavor. It also makes accurate sensing of input modalities beyond touch difficult. Therefore, prior research focused on mostly planar surfaces and basic tap and slide interactions. To overcome these limitations, this thesis concentrates on the emerging field of skin-worn devices. The proximity and conformality of these devices to the skin allow for usage on various body locations and sensing of novel input modalities, e.g. pressure, shear, and squeeze input.

Although on-skin electronics show a great promise for mobile computing, there remain many open questions from a human–computer interaction perspective:

- Can on-skin devices allow for robust touch input sensing on skin?
- Do they support various body locations and challenging body geometries?
- What are possible attachments for on-skin devices?
- Does on-skin input allow for expressive interactions, e.g. force input?
- Can on-skin devices support personalization in shape, size, and visual appearance?

To address these questions, we design and create three novel on-skin devices and their interaction techniques (Chapter 4, 5, and 6).

They are based on electronic skin, epidermal electronics, and soft deformation sensors. In contrast to prior studies on electronic skin in material sciences, we evaluate our touch-sensitive devices in user studies on the human skin. This takes the varying body characteristics, e.g. skin conductivity and capacitance, into account.

Furthermore, the findings show that the devices can conform to skin and be used on various body locations. In chapter 5, we show how our prototypes support challenging body locations, e.g. highly curved knuckles and narrow flexure lines.

We investigate the design space of stretchable on-skin devices from an human–computer interaction perspective and we present three novel device classes: wraps around body parts, attachments to wearable devices, and devices adhered to skin.

Prior work on electronic skin and epidermal electronics investigated contact-based input sensing. Our technical enabler support various input modalities on the human body: iSkin senses two levels of pressure (Chapter 4); SkinMarks supports touch, squeeze, and bend sensing with visual output (Chapter 5); ExpressSkin enables high-resolution pressure, shear, and squeeze sensing (Chapter 6). Taken together, these input modalities form a rich input vocabulary that can be used for expressive interactions, as it will be shown in the following chapters.

Finally, we show our skin-worn prototypes support various shapes and sizes to fit different people and body parts. We recognize aesthetics as an important property for on-skin electronics to improve the social acceptance of on-skin devices. Therefore we demonstrate the visually customization of our prototypes using digital fabrication.

4 | iSkin: Stretchable and Visually Customizable Touch Sensors

Skin is the largest human organ and can be used as a large input surface for mobile computing. In our study we observed the use of various body locations to distribute interactive elements for on-skin touch input. Prior research presented promising on-skin technology, but only investigated input on areas with low curvature, e.g. the forearm [69, 122]. However, many body parts, e.g. the finger, have a high curvature. Despite their potential, the curvature of the body and the softness of skin make accurate touch input a challenging endeavor.

We address these challenges by contributing *iSkin* [1]. iSkin is a novel, skin-worn input surface for on-skin interaction. It is a thin sensor overlay made out of biocompatible silicone. The sensor is flexible and stretchable to conform to the challenging geometry of the body. It is custom-shaped to fit the body location in shape and size. Figure 4.1 shows iSkin prototypes in five example applications. They demonstrate iSkin on various body locations and with three types of attachment: iSkin can be wrapped around body parts, be attached to body-worn devices, or adhere directly to the skin.

iSkin is "always available" and allows for fast and subtle interactions. It can be used either as a standalone input device 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 prior on-skin technologies. For example, iSkin can be wrapped around the finger for fast and direct input. The finger-worn sensor can be operated with the thumb of the same hand for single-handed input. The interactive elements can be placed on any location around the curved finger. Our implemented finger-worn sensor (Figure 4.1a) supports three touch buttons of the size of a fingertip and one linear slider with five elements. This demonstrates that iSkin supports body locations with high curvature and is stretchable enough to be worn over joints.

iSkin relates to the emerging stream of on-body interaction (see Section 3.2). It is technically based on advances in electronic skin (e-skin) and soft-matter electronics (Section 3.3). These are active research fields in robotics and material science. To our

[1] This chapter is based on a publication at ACM CHI'15 that I led as the main author [234]. I implemented the on-body touch sensing, designed the prototypes, derived the aesthetic design patterns, and conducted the evaluations. I contributed in the design of the layer composition of the touch electrodes.

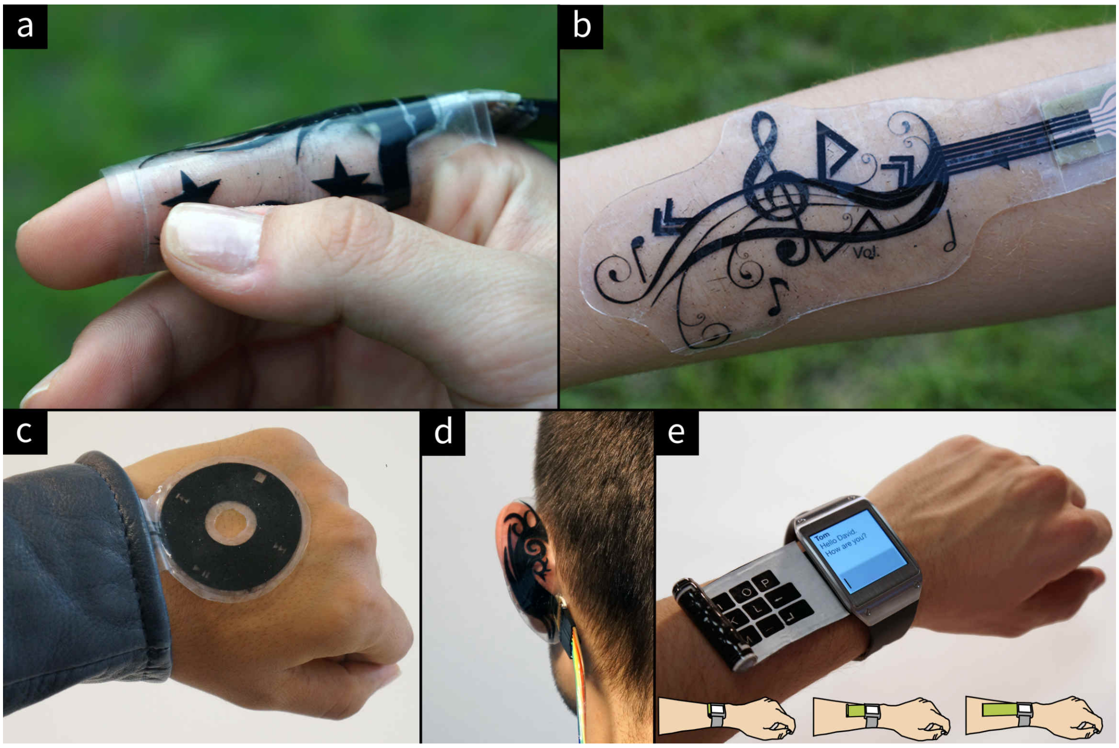

Figure 4.1: iSkin is a thin, flexible, stretchable and visually customizable touch sensor that can be worn directly on the skin. We present three novel classes of on-body devices based on iSkin: (a) *FingerStrap,* exemplified here with a strap on the index finger for fast, one-handed control of incoming calls. *SkinStickers,* exemplified here with (b) an input surface for a music player attached to the forearm, (c) a click wheel on the back of the hand, and (d) a headset control behind the ear. (e) *Extensions for wearable devices,* exemplified here with a rollout keyboard attached to a smart watch.

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. [141, 221]). Our sensing approach is visually customizable to support aesthetic designs; the conductive traces and electrodes act as (part of) the visual artwork. This chapter 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 4.1). These devices highlight different locations and contexts of use, different form factors, and different interactions.

The remainder of this chapter identifies design goals for skin-worn touch sensors (Section 4.1). Afterwards, we present the implementation of the sensor (Section 4.2) and discuss how to realize visually aesthetic sensors (Section 4.3). Finally, we show application examples (Section 4.4) and results from two evaluation studies (Section 4.5).

4.1 Design Goals for iSkin

This section details on requirements and opportunities for skin-worn touch sensors for mobile computing. Prior skin-worn devices were primarily proposed for robots, prosthesis, or medical devices. In contrast, the focus of iSkin is on-skin interaction for mobile computing. In the following, we introduce several dimensions for skin-worn sensors in the context of human–computer interaction. We detail on skin compatibility, promising locations, form factors, visual appearance, input and output capabilities, and interfacing with the sensor. These goals guide the design and implementation of the skin-worn sensors.

1. Skin Compatibility

The human skin is a complex organ as described in Chapter 2. The properties of skin should be taken into account, because skin-worn sensors can be in direct contact with skin for several hours or even days. Skin is soft and elastic (around 20%[192]) to absorb shocks and to allow for body movements. iSkin should mimic these properties, i.e. it should be soft, flexible, and stretchable, to be worn comfortably during mobile activities. Moreover, iSkin should not cause skin irritations and should not have any toxic effects when worn on skin.

In addition, iSkin should not interfer with the physiological functions of skin. iSkin should not restrict the breathing of skin and allow for evaporation of sweat through the sensor overlay. It should be either easily sanitizable, e.g. washable, or replaceable to limit the accumulation of pathogens and dirt on the sensor surface. The sensor should be as thin as possible to preserve tactile perception and to provide a high conformality to skin.

Skin properties do not only vary between people, but also from one body location to another: skin varies in thickness, presence or absence of hair, and sweat glands [76]. Hence, the used materials and adhesives need be able to cope with a large variety of skin properties to support different body locations.

2. Locations

The main goal of iSkin is to allow touch interactions on various body locations. Based on chapter 2 and chapter 3, we identify three locations that are highly promising for mobile interactions: arm, hand, and head.

Arm. The forearm and the upper arm are promising input surfaces for mobile computing: They provide a large input surface, are often not covered by clothing, and are easy to access. Prior studies have shown that the *forearm* is easy to access and socially acceptable to touch [223]. Furthermore, the forearm was the most preferred location for on-skin gestures in our elicitation study. It was used for 50.0% of all gestures (Section 2.3). The *upper arm* was only used for 4.4% of all gestures. However, it can increase the input space of arm-based interactions, e.g. by allowing access to infrequently used interactive elements.

Hand. The hand is a highly promising area for mobile computing. It has been used for 44% of all gestures in our study: 17.8% were performed on the palm, 18.9% on the back of the hand, and 7.3% on the fingers.

Sensors on the *palm* need to resist strong deformations, because the palm is often in contact with grasped objects. Interaction on the palm has been investigated for remote control [34], keyboards [225], gestures [226], and imaginary devices [58, 59].

The *back of the hand* is a relatively planar surface. Sensors on the back of the hand are less likely to conflict with grasp actions. The proximity to the wrist makes the back of the hand a promising input surface for smartwatches [147, 205].

Fingers are another promising location for mobile input. They contain a high concentration of tactile receptors and allow for single-handed interactions. Prior work investigated finger-worn devices for input on the fingerpad [20], fingernail [95], and visual output on the fingernails [211]. Their solutions augment a specific part of a finger, are rigid, and relatively thick. In contrast to these solutions, iSkin can be worn around the entire finger, including the joints.

Head. The head is another promising and often uncovered body location. Input on the face has been investigated by Serrano et al. [195]. Their users identified the cheek and forehead as preferred input areas for head-mounted displays [195]. Skin-worn devices can also be attached to less visible areas, e.g. behind the ear (see [125]).

Our application examples demonstrate that iSkin can be worn on all these locations.

3. Device Types and Form Factors

iSkin should be easy to attach and detach from the skin. The sensors should support various locations on the body, be robust to movements, and wear and tear. We identified three device types that differ in their attachment: wrapped around body parts, attached to body-worn devices, or adhere directly to the skin.

First, skin-worn devices can be wrapped around body parts. This attachment is similar to bracelets and rings (Figure 4.1a). However, in contrast to rigid electronics, our stretchable sensors can be worn close to or on joints.

Second, iSkin can be attached to other body-worn devices. It can be attached to smartwatches, bracelets, rings, or clothing. The flexibility and stretchability of iSkin allows for rolling and folding of the input surface. Hence, the size of the surface can be dynamically changed. For example, a highly portable, rollable keyboard can provide a large input surface for smartwatches (see Figure 4.1e).

Finally, iSkin can use skin-friendly adhesives to be adhered directly on the skin, similar to band-aids and temporary tattoos. This type of attachment supports various body locations. For example, it can be worn on the forearm, on the back of the hand, and behind the ear (Figure 4.1b–d).

For all three device types, iSkin should be customizable in shape and size to provide an exact fit to the body location. The sensors can be either customized at design time or support ad-hoc customization through cutting, as proposed by Olberding et al. [161].

4. Visual Appearance

Visual appearance is an important property for the social acceptability of wearable devices. iSkin should be mostly transparent to preserve the natural look of skin. In addition, non-transparent sensor parts should be visually customizable to enable aesthetically pleasing sensor designs. The designs of skin-worn devices could take inspiration from body adornments and body modifications, e.g. jewelry, tattoos, and make-up.

5. Input

iSkin should allow for fast and accurate input and avoid accidental activation. It can provide various input modalities, e.g. multi-touch, pressure, grab, scratch, pull, squeeze, shear, and twist input (see Section 2.3). iSkin currently supports the three most used modalities: multi-touch, pressure, and grab input. It is able to detect precise touch-down and touch-up events and distinguishes two-levels of pressure. Moreover, it supports multiple touch-sensitive electrodes on the same sensor. These can form more complex widgets, such as sliders and click wheels.

6. Output

iSkin provides static visual guidance to its user by visualizing interactive areas. The skin-worn devices can also feature visual output as presented in Chapter 5 and by Wessely et al. [238]. Future skin-worn devices could also integrate haptic feedback for subtle notification directly on the user's skin. Finally, iSkin can be connected to additional output devices, e.g. smartwatches, head-mounted displays, handheld devices, and public displays.

7. Interfacing and Processing

iSkin sensors need to be connected to a processing unit, e.g. a microprocessor. The processing unit supplies the sensor with energy, processes the output, and communicates the touch input to other mobile devices. Currently, these units cannot be produced in very thin, flexible, and stretchable form factors. Therefore, the processing unit needs to be based on rigid electronics. It can be embedded inside the thin iSkin sensor as a small, rigid button or attached to the sensor as a rigid clip. iSkin can also be tethered to a body-worn device, e.g. a smartwatch, to share its processing unit. In the long term, advances in thin-film electronics could enable thin and flexible processing units that would allow for fully flexible skin-worn devices.

Realizing skin-worn sensors that fulfill these seven goals is a challenging endeavor. Neither the rigid nor flexible electronics previously used in human–computer interaction allow for conformal skin-worn devices. Therefore, iSkin needs to be based on stretchable materials that previously have been used in robotics and material science (see Chapter 3.3). Moreover, it requires novel electrode designs for soft-matter electronics and sensing techniques that work reliable on various body locations. The next section presents the implementation of iSkin, which fulfills our seven design goals.

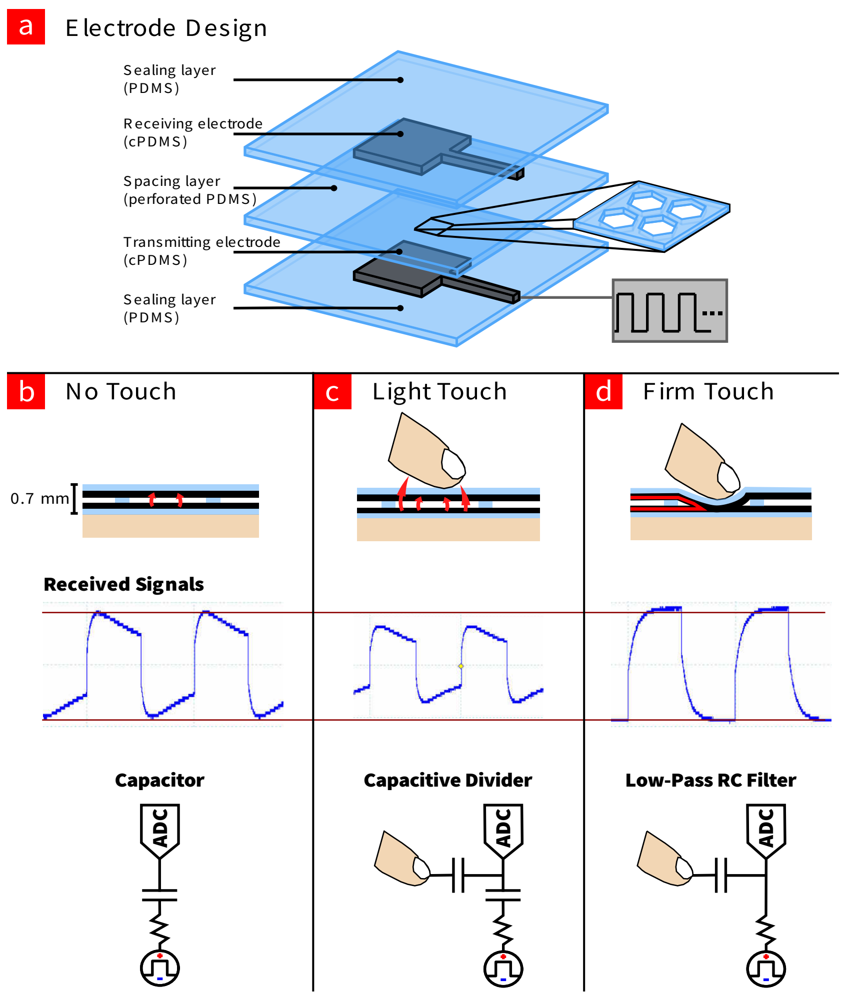

Figure 4.2: iSkin touch sensing: (a) overview of layers in a touch-sensitive iSkin, (b) sensing without touch contact, (c) projected capacitive sensing of slight touch events, and (d) resistive sensing of firm touch events.

4.2 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 (Section 4.2.1) and describe how to produce and process these materials in a simple lab environment (Section 4.2.2). Knowing about these materials might be helpful for the HCI community for realizing all sorts of elastic user interfaces beyond our specific sensor implementation. Then we contribute a sensor design for capacitive and resistive sensing of on-skin touch input (Section 4.2.3). 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.

4.2.1 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 [110], conductive meshes [70], or AgPDMS [132], cPDMS is inexpensive, 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 US$ 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.

4.2.2 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 by Lu et al. [132]. Figure 4.2 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 by Webb et al. [233].

4.2.3 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 $100\Omega m$ [150] 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 4.2a: 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 µm at areas where no electrodes or wires are laid out to approx. 700 µm 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.

Capacitive Sensing for Light Touch Contact

Projected capacitive sensing uses capacitive coupling between the two electrodes (Figure 4.2b). 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 4.2c). 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 4.2d). 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 4.2b–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 4.1a) and the EarSticker (Figure 4.1d), the click wheel as a WheelSticker (Figure 4.1c).

4.2.4 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 micro-controller. An additional transparent adhesive tape on the top of the connector further stabilizes it and avoids lateral shifting

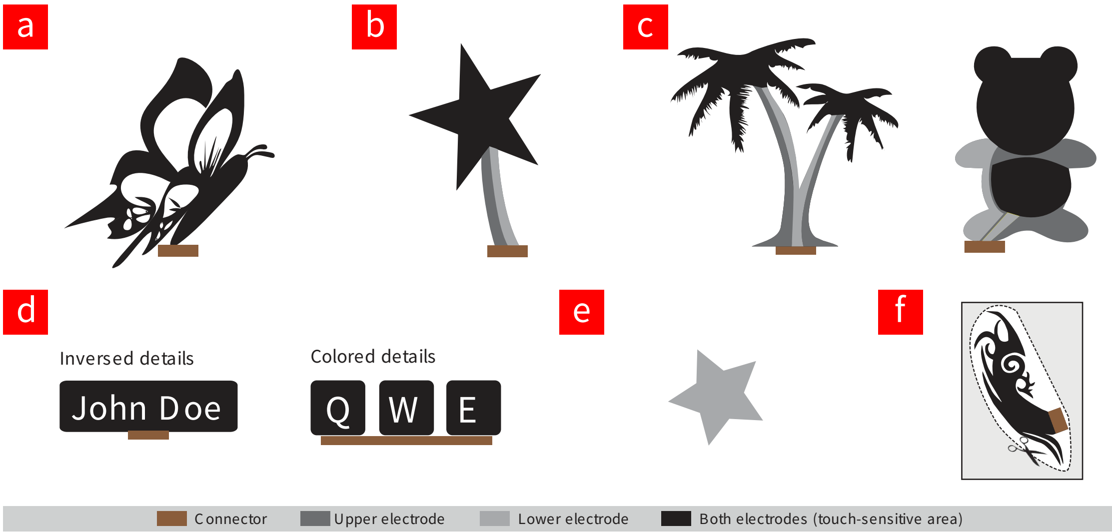

Figure 4.3: Design patterns for visual customizations: (a) fully touch-sensitive graphic, (b) partially sensitive graphic, (c) graphic with multiple interactive areas, (d) touch-sensitive detail using inverse and color patterns, (e) non-sensitive visual elements, and (f) shape customization.

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.

4.3 Design Guidelines of 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 [49], we contribute guidelines for the development of sensors which integrate aesthetics and electronic functionality. These patterns help designers to 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.

4.3.1 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 4.3a). 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.

4.3.2 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 in Section 4.3.1. 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 4.3b). Due to the close proximity of the top and bottom layers, both parts appear as a uniform solid shape to the human eye.

4.3.3 Graphic with Multiple Sensitive Areas

Multiple touch-sensitive areas within one graphic can each be directly connected with the connector through separate traces (Figure 4.3c left). Some interactive areas are only addressable by having their trace go through another interactive area (Figure 4.3c 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.

4.3.4 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 4.3d left). 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 colored layer of PDMS 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 4.3d right.

4.3.5 Non-Sensitive Visual Elements

It is possible to add insensitive visual elements, e.g. for aesthetic decoration (see Figure 4.3e), 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.

4.3.6 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 4.3f). This allows for a better fit on various body parts, but can also enhance the visual appearance of the sensor.

4.3.7 Summary

The above-mentioned patterns help designers to manually transfer a graphical design into a functional sensor. Figure 4.1 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.

4.4 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.

4.4.1 FingerStrap

The FingerStrap (Figure 4.1a) is a touch-sensitive film wrapped around the middle segment of the index finger to support microinteractions. Compared to ring-like devices, the strap 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. 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.

4.4.2 Extension for Wearable Objects

This prototype of a rollout keyboard can be attached to a smartwatch (Figure 4.1e). 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 4.1e. 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.

4.4.3 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 [235, 223]. 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 [80]. We show three SkinStickers for different functionalities:

MusicSticker. MusicSticker supports several functionalities in a visually aesthetic design, as shown in Figure 4.1b. It contains five interactive areas for controlling a music player: “Play”, “Previous”, “Next”, “Volume+”, and “Volume-”.

ClickWheel. We have implemented a ClickWheel sticker (Figure 4.1c). It captures circular rotation gestures. Moreover, touching and pressing on a segment differentiates between two commands.

EarSticker. Inspired by Earput [125], EarSticker (Figure 4.1d) 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.

4.5 Evaluation

In two evaluations, we investigated iSkin’s capabilities for on-skin touch sensing. In a technical evaluation, we demonstrate that iSkin remains sensitive to touch input when it is stretched and bent. Stretchability and bendability are important attributes for skin-worn sensors to support various body locations. In a user study, we evaluate the accuracy and robustness of iSkin when it is worn on three body locations. This user study provides evidence that the sensor is suitable for practical on-skin interactions.

4.5.1 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.

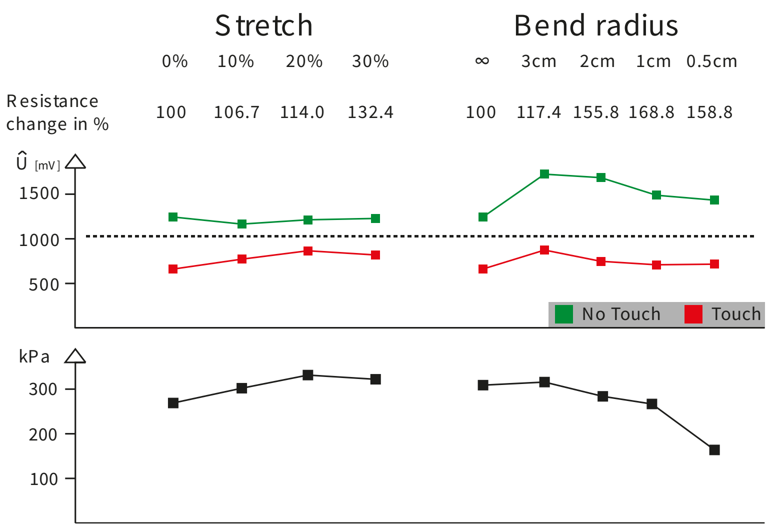

Figure 4.4: Results of the technical evaluation: (a) relative change in resistance, (b) measured voltage $\hat{U}$ for capacitive touch contact and no touch, and (c) required pressure for resistive touch contact.

Figure 4.5: Study setup on the participants' forearm, back of the hand and finger. Two straps of Velcro allowed for fast and easy attachment.

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 4.4 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 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.

4.5.2 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 [28]. It was attached directly on the user's skin using two straps of Velcro (see Figure 4.5). 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.

4.6 Limitations

While it has been shown that the present design suffices for novel application-specific designs for touch input on the skin, important challenges remain: (1) size and resolution of touch input, (2) visual output, and (3) continuous pressure input. These will be addressed in the following chapters of this thesis.

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 ≈ 15 [28]) 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 cross-talk 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. Our sensor can simultaneously sense multiple touch contacts, making it suitable for use with multi-touch interfaces once the resolution increased. The number of available pins on the controller board could be easily increased by using multiplexers.

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 trace width). One solution would be to use AgPDMS or PEDOT:PSS instead of cPDMS. The principles introduced in this chapter transfer to both materials. The next chapter addresses these limitations by presenting a different fabrication approach for skin electronics using screen-printed PEDOT:PSS. This allows for smaller conductive traces and interactive areas with a width of 0.25 mm. It also supports interpolation between electrodes, as shown with the example of a two-electrode slider sensor designs.

Second, future iSkin could also provide visual output through an embedded thin-film display. It has been shown that customized and deformable thin-film displays can be easily fabricated [160], but they do not conform to the challenging geometry of the body. Chapter 5 presents very thin electroluminescent displays for on-skin interfaces.

Third, *continuous pressure* is another dimension to consider. The high and inhomogeneous resistance of cPDMS makes it 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. Chapter 6 investigates continuous and high-resolution pressure, shear, and squeeze input. The presented soft prototypes are thicker than iSkin, but allow for exploration and evaluation of novel interaction techniques.

4.7 Conclusion

This chapter contributed the design of a novel class of skin-worn touch sensors. iSkin builds on and extends recent advances in research on electronic skin. We detailed on the fabrication of iSkin. Our sensors are based on thin, flexible, and stretchable silicone layers with embedded carbon-doped electrodes. We also contributed general design patterns to customize the visual aesthetics of functional touch sensors. Finally, we showed that iSkin allows for accurate touch sensing on the skin and demonstrated its usage for mobile computing with our prototypes.

iSkin advances the field of on-skin interaction by supporting precise touch and pressure input on various body locations. Both are important properties of on-skin interaction according to the findings of our elicitation study (see Section 2.4).

First, iSkin allows for interaction on *various body locations*. Our fabrication approach supports customization of the sensor's shape and size to fit different body parts. The thin, flexible, and stretchable form factor allows it to be worn on challenging locations with high curvature, e.g. the finger and the back of the ear. A technical evaluation showed that this solution supports bending around radii of 5 mm and stretching by 30%. Hence, iSkin is well suited for on-body interaction on various locations.

Second, iSkin extends the *input expressivity* by detecting multi-touch and force input. It accurately measures precise touch-down and touch-up events of one or multiple fingers. Beyond conventional *multi-touch* input, iSkin distinguishes between light and firm touch events. Hence, it supports two states of *pressure* as a skin-specific modality. Multiple touch-sensitive electrodes can form more complex widgets, such as sliders and click wheels. They also allow to distinguish the touch of a fingertip from the grab of a hand. Therefore, iSkin senses the three most used input modalities of our study (touch, pressure, and grab input).

Taken together, iSkin advances on-skin interaction towards expressive on-skin input on various body locations. The next two chapters contribute towards that goal by investigating input on highly challenging body locations using highly conformal skin-worn electronics (Chapter 5) and by contributing expressive interaction techniques using high-resolution force input (Chapter 6).

5 | SkinMarks: Interaction on Body Landmarks

The human body has various types of landmarks, which are distinct from their surroundings. These landmarks offer 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. [58, 59], 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 chapter contribute our definition of *body landmarks*: visual and tactile distinct locations on the body that can support and ease on-skin input. Based on this definition, we identify five types of body landmarks: skeletal landmarks, skin-microstructures, elastic landmarks, visual skin landmarks, and passive accessories. These landmarks promise to be beneficial for on-skin interaction. However, prior on-skin technologies were unable to use these benefits, because the curved geometries and narrow shapes of these landmarks were too challenging for existing on-skin sensors.

We enable such on-skin interaction by contributing *SkinMarks* [1]. SkinMarks is an enabling technology for interaction on body landmarks. Its technology is inspired by recent advances on epidermal electronics (Chapter 3.3.2). SkinMarks are highly conformal interactive tattoos, which enable precisely localized input and output on the five types of body landmarks. The high conformality is achieved by reducing the thickness of the skin-worn electronics. SkinMarks allows for a magnitude thinner touch sensors (4 µm) compared to iSkin (700 µm; Chapter 4). We extend the input expressivity by supporting touch, squeeze, and bend sensing with integrated visual output. SkinMarks are compatible with strongly curved, elastic, and tiny body landmarks that have not been investigated with prior on-skin technologies. These make it possible to use the tactile and visual cues of body landmarks for direct, eyes-free, and expressive interaction.

[1]This work is based on a publication at ACM CHI'17 that I led as a main author [236]. I contributed significantly to the design of SkinMarks [236], in deriving the types of landmarks, and their interactional benefits. I led the fabrication of SkinMarks and the conformality evaluation.

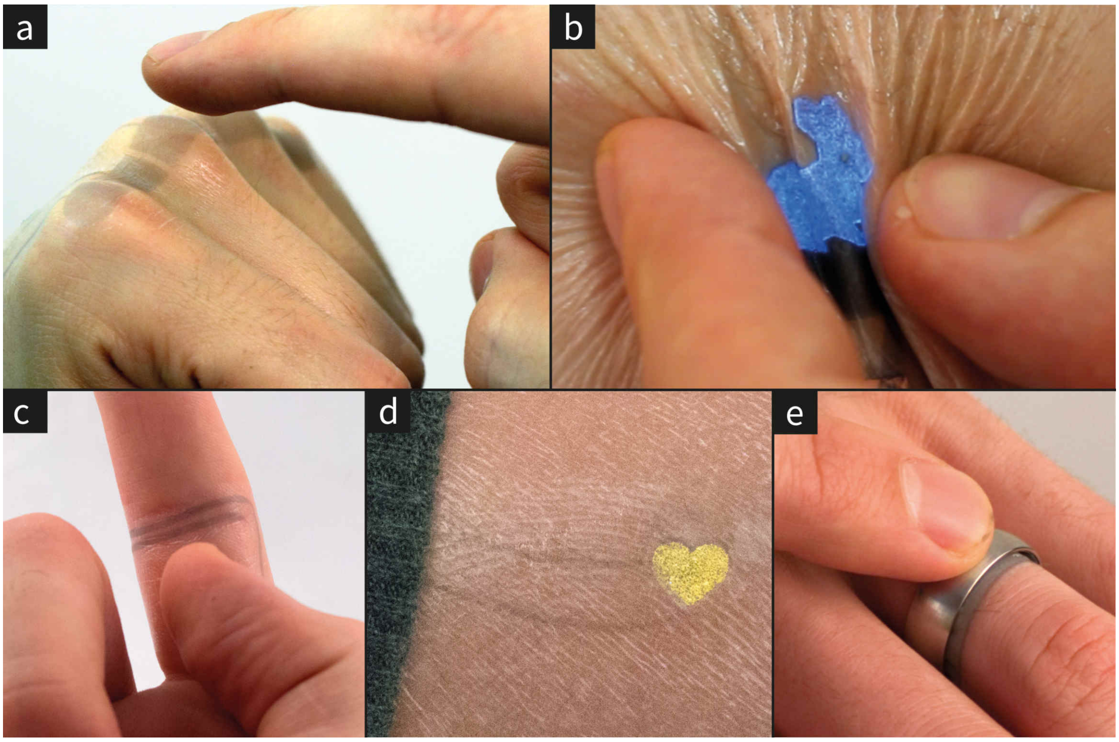

Figure 5.1: SkinMarks are conformal on-skin sensors and displays. They enable interaction on five types of body landmarks: (a) skeletal landmarks, (b) elastic landmarks, (c) skin microstructures, (d) visual skin landmarks, and (e) accessories.

The contributions of this chapter 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 interaction 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.

The remainder of the chapter introduces and identifies body landmarks (Section 5.1). Next we present the implementation of SkinMarks (Section 5.2) and present novel interactions on body landmarks (Section 5.3). Finally, we evaluate the conformal form factor and the precise localization of touch-sensitive temporary tattoos (Section 5.4).

5.1 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*.

5.1.1 Benefits for On-body Interaction

Body landmarks can offer the following three 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 example, 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.

5.1.2 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 [37] and body adornments [29].

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 [34, 58, 59, 156, 225]. 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 [108]. 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 typically be easily located on the body and can offer distinct physical affordances for interaction; e.g. a ring can be touched and rotated [4].

5.2 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 (Section 5.2.1). Then we detail on our technical contributions to make SkinMarks conformal on challenging geometries (Section 5.2.2). Finally, we describe the implementation of precisely localized, co-located input and output surfaces for sensing of touch (Section 5.2.3), bend and squeeze input (Section 5.2.4), and for visual display (Section 5.2.5).

5.2.1 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 [160].

To fabricate an interactive tattoo, we use commercially available temporary tattoo paper (Tattoo Decal Paper) as the substrate, as proposed in recent work [96, 127]. 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.

5.2.2 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 [90]) 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 [127], 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 ($\approx$16 µm [127]). 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 [96] or gold leaf [127]: it is intrinsically stretchable [123]. This does not only make the conductor conform better to challenging geometries; it also makes it considerably more robust to mechanical strain [123]. To further improve the robustness, we recommend laying out conductors in a horse-shoe pattern [78] 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 5.2).

5.2.3 Touch Sensing

Touch has been identified as an important input modality for on-skin electronics [234, 127, 96]. Solutions from prior work used fingertip-sized electrodes [234, 127, 96]. Body

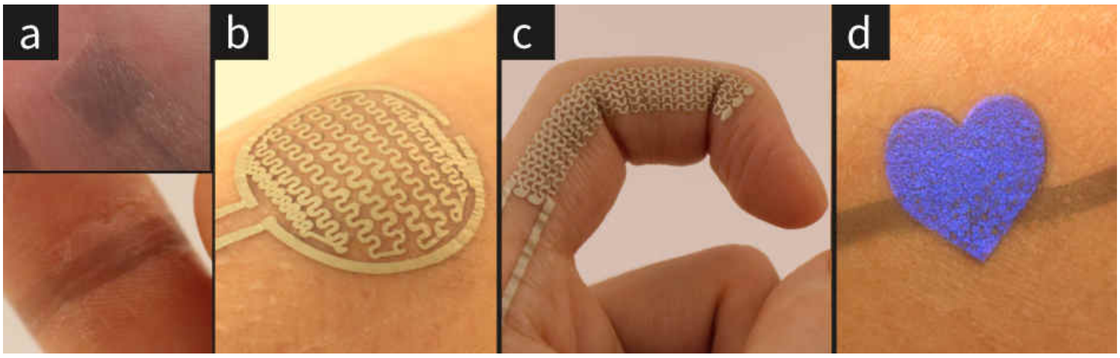

Figure 5.2: SkinMarks supports: (a) capacitive touch buttons and sliders, (b) squeeze sensors, (c) bend sensors, and (d) electroluminescent displays.

landmarks 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 5.2a). 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 [28].

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 [96, 127, 234].

5.2.4 Squeeze and Bend Sensing

Skin allows for deformation input as a a further modality for tactile on-body interactions, as recommended in [235]. 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 5.2b) 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 [28]. 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 [127]. 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 5.2c).

5.2.5 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 [96] and are considerably slimmer than prior body-worn light-emitting diodes [127] and EL displays [238]. 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 5.1c, 5.2d, and 5.4).

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 [160]. 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 [160]. 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 [160].

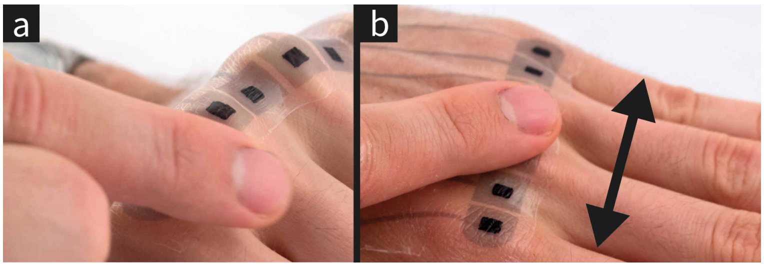

Figure 5.3: Interaction on challenging, highly curved skeletal landmarks: (a) tapping the peaks and valleys for discrete input; (b) sliding along the knuckles for continuous input.

5.3 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.

5.3.1 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.

We demonstrate these benefits for on-body interaction by deploying a touch-sensitive SkinMark sensor on the knuckles (Figure 5.3). 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 5.3).

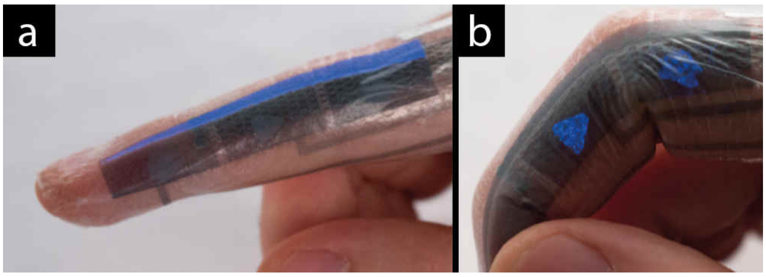

Figure 5.4: Using body posture to dynamically change functionality: (a) Straight finger for linear movements, e.g. to control volume. (b) Bent finger for discrete touch areas.

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 5.4). 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 5.4a). 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 5.4b).

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.

5.3.2 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 music player.

The wrinkle slider contains two triangular printed electrodes, which together measure 30×4.5 mm (Figure 5.5a). 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.

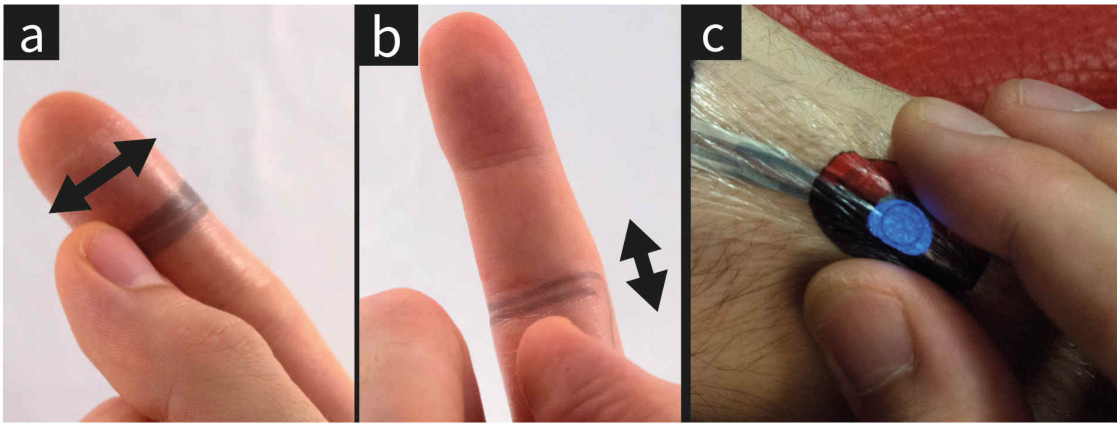

Figure 5.5: SkinMarks allow for precise touch input on skin microstructures: (a) wrinkle slider and (b) wrinkle toggle. (c) Interacting on an elastic landmark.

A similar sensor design allows for toggle input (Figure 5.5b). 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.

5.3.3 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 5.5c). The CaptureMark 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.

5.3.4 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 implemented a *HeartMark* (Figure 5.6b), 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.

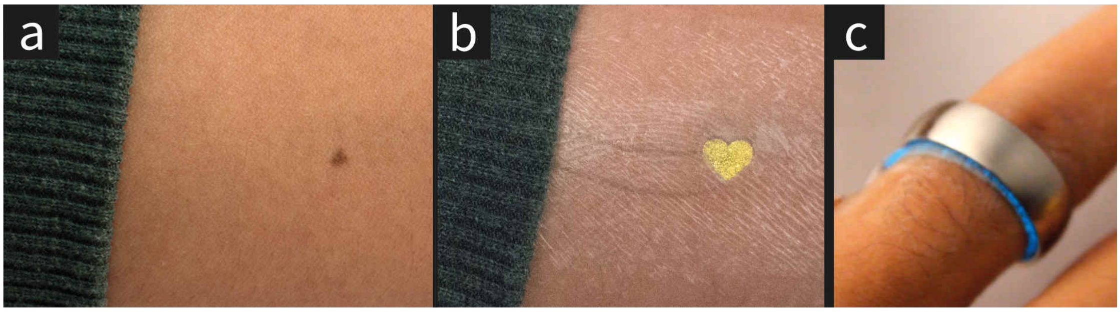

Figure 5.6: SkinMarks can augment visual skin landmarks, e.g. birthmarks (a–b), and passive accessories, e.g. a ring (c).

5.3.5 Interaction on Passive Accessories

Body-worn passive accessories can function as landmarks 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 [168]. Second, it can make accessories touch-sensitive, through capacitance tags [176]. 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 5.6c), 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.

5.4 Technical Evaluation

This section presents results from technical experiments that investigate the two key technical contributions of SkinMarks:

1. Do SkinMarks support interaction on challenging landmarks by *conforming to skin* despite high curvatures and strong elasticity?
2. Do SkinMarks allow for *precisely localized interaction* on fine landmarks?

5.4.1 Conformal Form Factor

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

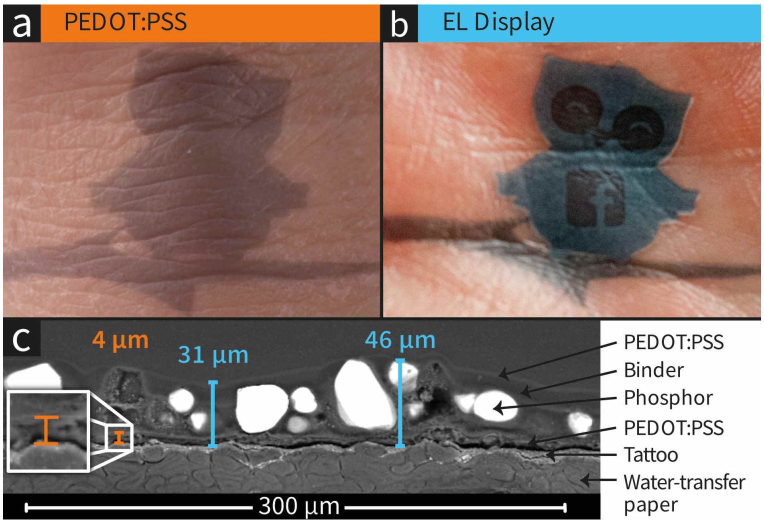

Figure 5.7: SkinMarks conform to wrinkles: (a) a tattoo with PEDOT:PSS conductor and (b) a tattoo with EL display. (c) Cross-section of a tattoo with printed EL display, taken with a scanning electron microscope (SEM).

To investigate the layer thickness of printed inks on a SkinMark, we analyzed cross-sections of printed SkinMark tattoos on the water-transfer paper with a Scanning Electron Microscope (SEM). Figure 5.7 shows the various layers of inks. A layer of PEDOT:PSS layers is approximately 1 µm thick (≈4 µm with tattoo paper). A full TFEL display is between 31 µm to 46 µm thick (Figure 5.7c). These numbers demonstrate the vastly reduced display thickness compared to prior interactive tattoos [96, 127] and TFEL displays [160, 238]. Figure 5.7 a&b illustrate how SkinMark tattoos closely conform to wrinkles. Our results confirm prior research of Jeong et al. [90], which show that elastomer membranes of 5 µm have excellent conformality even to small wrinkles, while membranes of 36 µm 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 [123]. For comparison, the stretchability of the human epidermis is around 20% [192]. The combination of both makes SkinMarks intrinsically stretchable and more robust against strain than metals (e.g. [96, 127]).

5.4.2 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

In a user study, we investigate the accuracy of touch sensing on the skin with 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 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 [28].

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 birthmarks (visual skin landmark). The order of presentation of tattoos was counter-balanced. The tattoos had fine target points (see Figure 5.8). 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).

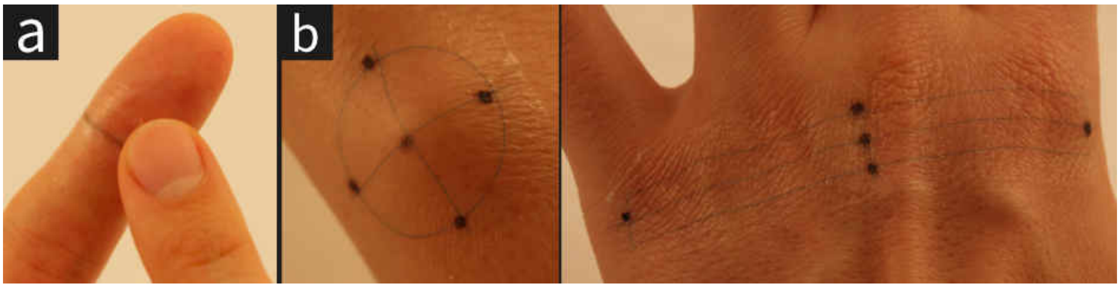

Figure 5.8: Study setup: (a) evaluation of touch on sub-millimeter electrodes and (b) of precise tattoo application.

5.5 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 and 3.5 hours. Preparing the screen printing mask took the longest time ($\approx$ 2.5 hours). 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. 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 µm). 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.

Safety. Electroluminescent displays are driven using high-voltage, but low alternating current (AC) [160]. 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 µm). This approach also ensures that ink does not contact the user's skin. According to prior work [56], 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 recommend 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.

Additional Landmarks. While the five types of landmarks introduced in this chapter 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.

5.6 Conclusion

This chapter investigated body landmarks for on-skin interaction. We identified five types of body landmarks that provide tactile and visual cues to benefit and ease on-skin interaction. We enabled interactions on body landmarks by contributing *SkinMarks*, a technical enabler for interaction on small, highly curved, and deformable body landmarks. SkinMarks are stretchable and have a very slim form factor. Therefore, they are able to conform to irregular geometry, like flexure lines and protruding bones. We introduced five types of body landmarks that are supported by our technology. Finally, we demonstrated novel interactions on each of these landmarks to advance on-body interaction towards more detailed, highly curved, and challenging body locations.

This chapter extends the prior chapter in two ways to support our goal of expressive interaction on various body locations: First, it adds body landmarks to the set of supported *locations* for on-skin interactions. Body landmarks include highly-curved, narrow, and deformable skin areas. This allows the use of visual and tactile cues of skin for on-skin interactions. Therefore, this chapter expands the interaction space of on-skin input toward more detailed interaction on challenging body areas. Second, this chapter is a step forward towards support of novel skin-like modalities to increase the *input expressivity*. SkinMarks supports sensing touch on sub-millimeter electrodes, captures squeeze and bend input, and supports active visual output.

6 | ExpressSkin: Expressive Force-based Interaction Techniques

This chapter advances the input expressivity of on-skin devices by investigating three input modalities: pressure, shear, and squeeze input. The three input modalities are all based on force input and have been used by participants in our study (see Chapter 2.3). Each input modality can vary in the amount of exerted force, as well as, in the force direction. This chapter investigates possibilities and benefits of these force-based input modalities in novel interaction techniques for mobile computing.

We present ExpressSkin [1], a skin-worn sensor to investigate force-based interaction techniques (Figure 6.1). ExpressSkin is a soft and skin-like input surface. It consists of a deformable silicone dome based on silicone, an infrared LED, and four photodiodes on the sensor base. Force input of the finger deforms the surface of the dome, which can be measured through the changes in the amount of reflected light. In its current implementation, ExpressSkin is not stretchable, and it is a few millimeters thick to allow for precise measurements. To ensure a high wearability on various body locations, ExpressSkin has a small and soft form-factor.

ExpressSkin senses continuous and high-resolution input based on three modalities: pressure, shear, and squeeze. Hence, its sensing capabilities exceed the input expressivity of iSkin (two levels of pressure, Chapter 4) and SkinMarks (binary squeeze input, Chapter 5). Furthermore, the integration of the three input modalities into the same input surface allows for fluid interactions in a large, multi-dimensional interaction space. Based on this input, we investigate novel interaction techniques for mobile computing.

The form factor and expressive input capabilities of ExpressSkin are also highly desirable for miniaturized wearable electronics. Such wearable devices could be as small as the head of a push pin. These devices would be highly mobile, comfortable to wear at a multitude of locations on the body, unobtrusive, and well-suited for fast and discreet mobile interactions [149]. They could be used as a tiny standalone input device with audio or haptic feedback, as an easy-to-reach input surface for head-mounted displays,

[1] This chapter is based on a publication in ACM IMWUT that I led as the main author [237]. I led the design of the device concept, implemented the setup and evaluated the user studies, investigated and implemented squeeze sensing, and developed the interaction techniques.

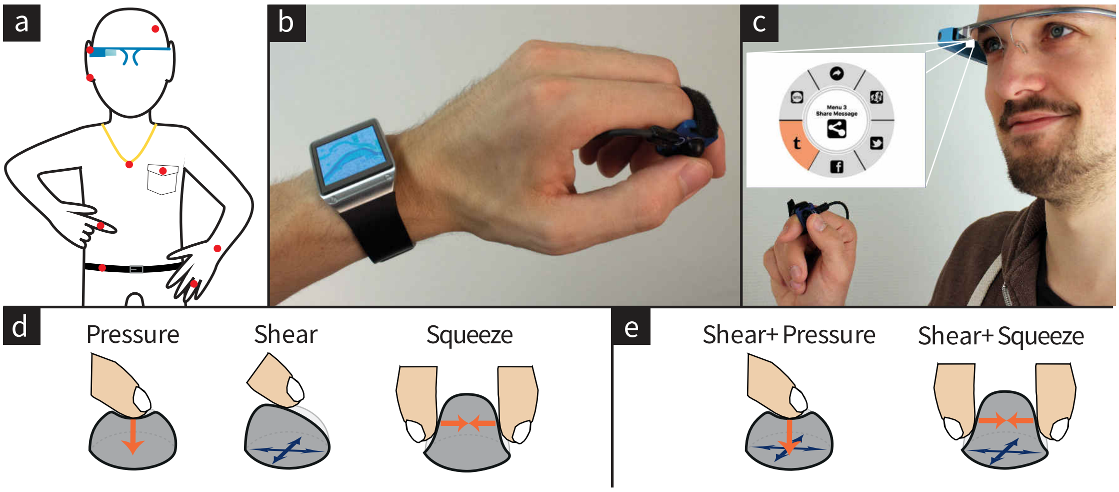

Figure 6.1: (a) ExpressSkin enables expressive force-based input on various body locations: (b) one-handed input for smartwatches, (c) discreet input for head-mounted displays, (d) force input primitives, and (e) their fluid combinations.

or for occlusion-free input in close proximity of small body-worn displays. We recognize this potential by proposing the integration of skin-like force sensors into grasped objects, e.g. a graspable pendant.

This chapter presents three primary contributions:

First, we introduce ExpressSkin, a *novel class of tiny and expressive wearable input devices* that use pressure, squeeze, and shear input. Their tiny form factor supports a variety of different body locations. We describe the interaction space for tiny force-sensitive wearables, illustrate possible locations for ExpressSkin, and demonstrate the technical feasibility with three functional device prototypes: a finger-worn device, a wrist-worn device, and a pendant (see Figure 6.2).

Second, we illustrate the capabilities of ExpressSkin by contributing a set of *force-based interaction techniques for tiny wearable devices*. The techniques enable fluid interaction in a large input space by combining multiple dimensions of forces, mitigating input problems on existing wearable devices. For example, ExpressSkin allows for fluid, one-handed navigation on smartwatches, for interaction in a large gesture space, and for discreet menu selection. We demonstrate the interaction techniques in six application examples, showing ExpressSkin as a standalone input device and as a companion device for smartwatches, head-mounted displays, or headphones.

Finally, we report *empirical findings on force-based input on tiny wearable devices* from a controlled experiment with users. The findings detail on the performance of three devices worn on different body locations (finger, wrist, and graspable pendant), both in standing and walking conditions. The results show that pressure, shear, and squeeze forces enable fast and precise input. The participants were able to distinguish and hold up to six force levels in each direction. Furthermore, combined pressure and shear, as well as, combined squeeze and shear forces can be performed simultaneously, which allows for fluid and multi-dimensional input. The results also demonstrate large effects of one-handed vs. two-handed interaction in walking conditions, which has important implications on the choice of an appropriate body location and device form factor for ExpressSkin input. We conclude by providing design recommendations for wearable devices with multi-dimensional force input.

The remainder of the chapter introduces the concept of ExpressSkin (Section 6.1). Next we detail on the implementation of ExpressSkin (Section 6.2) and present novel interaction techniques using multi-dimensional force input (Section 6.3). Finally, we report findings from an user study (Section 6.4) and discuss implications and design implications for ExpressSkin and their interaction techniques (Section 6.5).

6.1 ExpressSkin Concept

ExpressSkin proposes expressive force input on a tiny form factor. This opens up a novel and unexplored design space for skin-worn wearable devices. In the following we detail on the rational behind ExpressSkin's form factor (Section 6.1.1), detail on body locations (Section 6.1.2), and the primitives of force input on tiny surfaces (Section 6.1.3).

6.1.1 Form Factor and Size

ExpressSkin input devices are tiny wearables that have an input surface *smaller than a fingertip*. They offer a *soft* input surface that can be continuously deformed in different ways and strengths. The sensing principle behind ExpressSkin would allow for a completely flat input surface. However, we chose a *slightly protruding* sensor surface to provide tactile cues. The tactile feedback on the interacting fingertips can help to locate the input surface. Furthermore, the slightly angled contact points ease the force input and allows for a better grip. Due to the tiny input surface, ExpressSkin can be designed to be visually unobtrusive, which supports social acceptability. For example, it can be worn as a small artificial birthmark, while allowing for expressive mobile interactions. Furthermore, input can be discreet, since force input does not require large movements or gestures.

6.1.2 Body Locations

The radical form factor allows ExpressSkin to be worn at many body locations for always-available interaction. Figure 6.1a shows various possible locations. They can be integrated as small, soft and skin-like interactive elements into larger skin-worn electronics (e.g. the devices in chapter 4). Furthermore, the form factor is highly compatible with a large variety of existing body-worn objects, including jewelry (e.g. pendant, ring, earring), accessories (e.g. buttons, bracelets), piercings, and existing wearable devices (e.g. smartwatches, head-mounted displays, in-ear headphones, and fitness trackers).

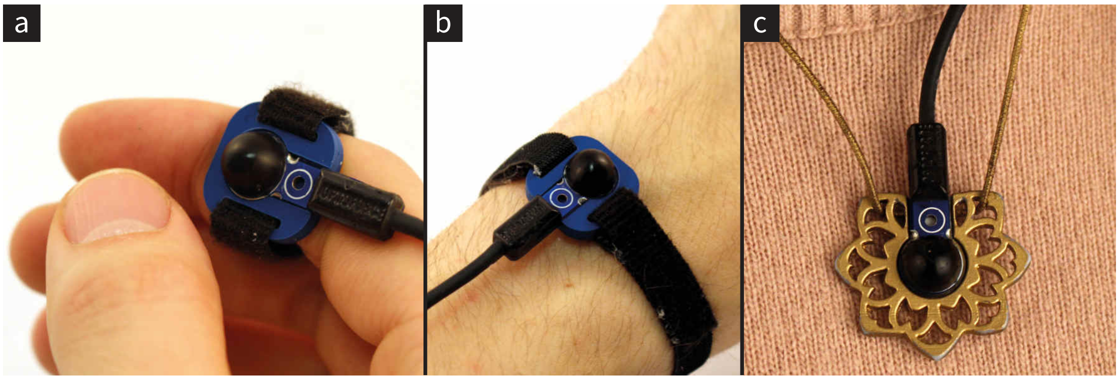

Figure 6.2: Functional ExpressSkin prototypes: (a) finger-worn devices, (b) wrist-worn devices, and (c) aesthetic pendant.

From the large space of supported locations, we chose three input locations to be investigated in more detail. They were inspired by common locations for on-skin interaction and body-worn wearables [149, 208] These locations highlight important body areas, device form factors and allow us to study different interaction styles, most notably one-handed vs. two-handed interaction.

Input on the Finger

The tiny surface of ExpressSkin allows for one- and two-handed input on the small surface of a finger, e.g. by integrating it into a ring (Figure 6.2a). A well-suited location is the middle segment of the dominant index finger, with the input surface facing towards the thumb. This location offers ergonomic access [85] and avoids interference with grasping. Compared to prior solutions for touch input on the finger [20, 21, 95], ExpressSkin input is not restricted by the size of the surface, nor does it require finger displacement.

Input on the Wrist

ExpressSkin input can be integrated into wrist-worn objects (Figure 6.2b) to enable fast and expressive interactions. The wrist is a frequently used location for body-worn accessories (e.g. bracelets, cuff buttons) and wearable devices (e.g. smartwatches and fitness trackers). It is quick and easy to access by the fingers of the other hand. For instance, integrated in a cuff button (Figure 6.3), it can enable direct-to-access and expressive interactions for head-mounted displays. Added on the bracelet of a smartwatch, it enables occlusion-free input.

Input on a Graspable Pendant

ExpressSkin can be integrated into jewelry and accessories that are loosely attached on the body. For instance, it can be integrated into the pendant of a necklace (Figure 6.2c). The location at the chest is fast to access, convenient to grasp, and a common location for jewelery for men and women. The loose attachment of the pendant allows the user to hold the input device using a comfortable posture. For example, the pendant can be

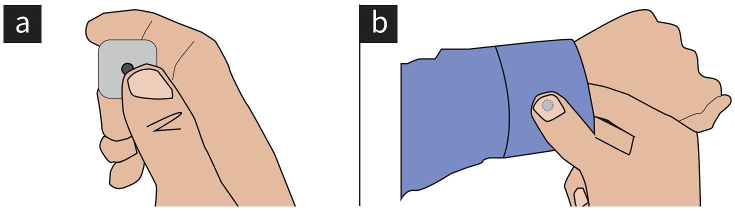

Figure 6.3: ExpressSkin supports input on tiny wearable objects (a) and could be embedded into clothing (b), e.g. as a cuff button.

grasped with one hand for one-handed thumb input. Alternatively it can be held with one hand and interacted on using the fingers of the other hand. Other loosely attached graspables, e.g. headphone cables, can be used in similar ways.

6.1.3 Force Input

The force input of ExpressSkin offers a large, continuous input space. The fingers interact around a single device point, with little finger displacement, by exerting small forces. The ExpressSkin device senses three force input primitives simultaneously. All of them can be performed in one-handed or two-handed interactions (Figure 6.4).

Pressing. Pressure forces are created when the user presses onto the ExpressSkin sensor using the thumb or another finger (Figure 6.4a). Our prototypes support continuous pressure forces from 0 to 5 N. This fully covers the typical forces exerted by fingers.

Shearing. Shear forces are created through a tangential force that the thumb or finger exerts on the upper side of the sensor (Figure 6.4a). Shear offers a rich two-dimensional input channel. Shear forces contain two parameters: the force (0–5N) and the direction of the force (0–360°).

squeezing. squeeze forces are created by squeezing the ExpressSkin sensor with the thumb and a finger. This creates opposed compressive forces on the sides of the sensor (Figure 6.4b). Our prototypes measure continuous squeeze forces up to 5N.

The precision of three-dimensional force input allows for a high degree of expressiveness on a tiny input surface. Combinations of the three force input primitives further create a rich multi-dimensional input space. Lastly, tactile feedback about the force and its direction support the user, without requiring visual attention.

6.2 Implementation

This section describes the sensing principle of ExpressSkin and the implementation of three wearable prototypes.

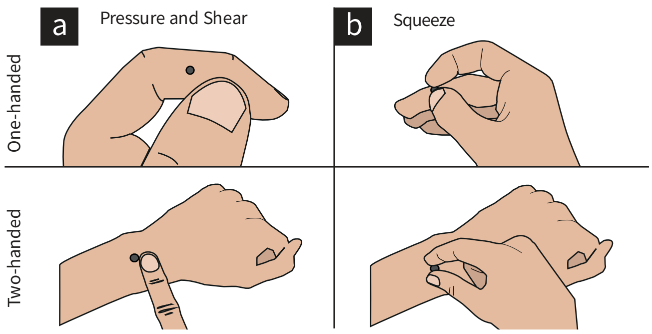

Figure 6.4: ExpressSkin supports one-handed and two-handed input: (a) pressure and shear input; (b) squeeze input.

6.2.1 Force Sensing

ExpressSkin uses optical force sensing to measure three-dimensional forces on the soft, elastic surface. An infrared LED in the middle of the sensor illuminates the inner structure of the hemisphere. The reflected amount of light is measured using four light-sensitive photodiodes [215]. The intensity of the reflected light can be mapped to continuous forces. For instance, when the finger presses on the top of the sensor, the distance between diodes and surface decreases, resulting in a higher light intensity (Figure 6.6a). During shear, the distance between diodes and surface changes asymmetrically, e.g. shearing to the left increases the distance for the left diode while it decreases the distance for the right diode (Figure 6.6b).

We implement this approach using a force-sensitive sensor that is developed for industrial robots (OptoForce OMD-10-SE-10N, see Figure 6.5). Our experiments showed that the sensor is also well capable to sense forces created by a human finger (Figure 6.6a-c). The sensor covers the typical force range of the hand (approx. 5 N). The sensor has a high resolution (2.5 mN), and low energy consumption (10 mA). It has a small non-linearity (2-5%), small crosstalk between diodes (5%), and small hysteresis (<2%). The sensor sends the four diode's intensity values, filtered using a 15Hz low-pass filter, via USB at 100 Hz. These properties enable precise force input for wearables.

The sensor measures the pressure and slippage forces. These forces directly map to ExpressSkin *pressure and shear forces*. However, by default the sensor only captures 2.5 dimensional input: an opposed input to pressure is not supported. This would considerably limit the capabilities of such an input device for HCI.

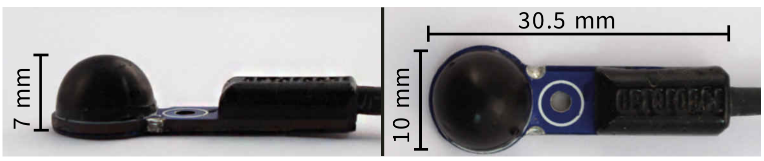

Figure 6.5: Sensor used in our prototypes

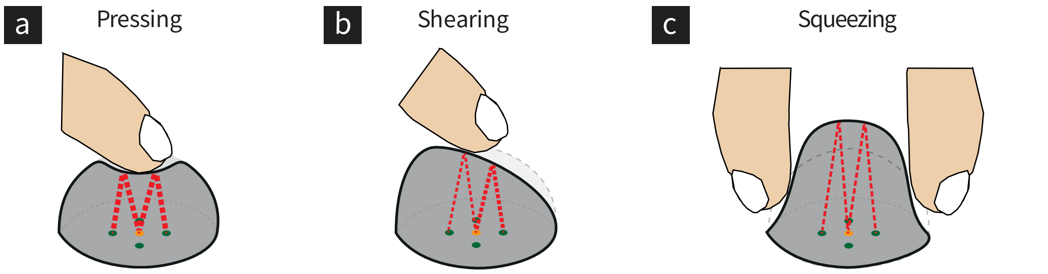

Figure 6.6: Force sensing using four light diodes: (a) pressure increases the amount of measured light on all diodes, (b) shear changes the amount of measured light asymmetrically, and (c) squeeze decreases the amount of measured light on all diodes.

We address this issue by contributing a sensing technique for capturing squeeze input. squeeze forces have not been previously studied on this class of sensors. By inspecting the sensor's raw values, we found that a squeeze results in a unique sensor response. A squeeze presses two opposite sides of the sensor towards the center; hence, the distance of all diodes to the surface *increases* (Figure 6.6c). The decrease in the diode reading created by a squeeze forces can be measured using the following equation:

$$D = \frac{\sum_{i=1}^{4} (\beta_i - S_i)}{4}$$

where S_i is the raw reading of diode i and β_i is its baseline value in the rest state when the sensor is not deformed.

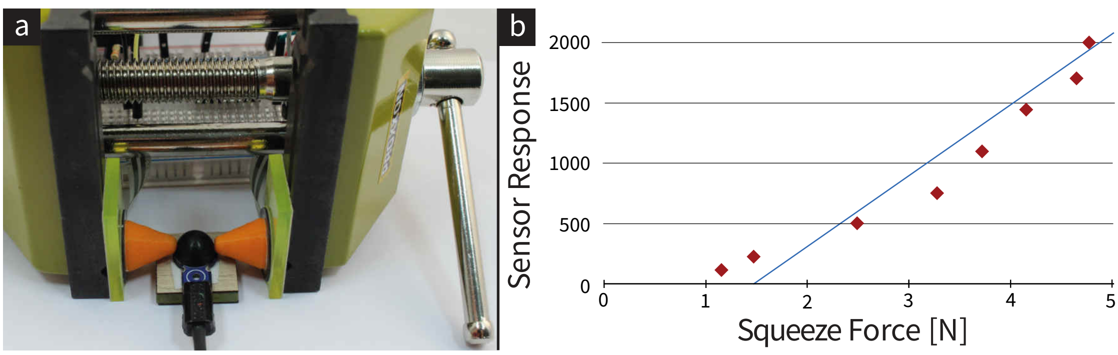

Figure 6.7: Evaluation of squeeze forces: (a) apparatus and (b) sensor response for squeeze forces with a fitted linear mapping function.

In a *technical evaluation*, we studied the sensor's characteristics for squeeze forces. We built an evaluation setup to apply symmetrical forces on both sides of the sensor (Figure 6.7a). The forces were measured by two force-sensitive resistors (FSR 402). A 3D printed cone connects a 5 mm tip with the force-sensitive area on the FSR. Figure 6.7b shows the relation between squeeze forces and the sensor response D using the formula above. The plot shows a continuous sensor response and a high dynamic range. A linear function showed a good fit to the sensor data ($r^2 = 0.935$) and is used as a continuous mapping function. However, it must be noted that very low squeeze forces (<1 N) cannot be precisely captured. As such small forces generated a slight deformation of the sides of the sensors, the center of the hemisphere, where the diodes are measuring the signal, remained virtually undeformed. This could be improved in future implementations by a slight readjustment of LEDs and photodiodes, such that they directly capture the deformations of the sides of the hemisphere. Overall, the evaluation shows that continuous squeeze input can be captured with a high resolution. Hence, the same sensor hardware can be used to capture three types of forces and to enable full three-dimensional input.

6.2.2 Prototypes

We realized functional prototypes of three ExpressSkin devices: a finger-worn device, a wrist-worn device, and a pendant (Figure 6.2). The prototypes feature small form factors with a fingertip-size hemispherical input surface ($\oslash$10 mm, Figure 6.5). The contact area between the finger and the hemisphere has a diameter of approx. 6 mm. The surface is made of deformable silicone.

The *finger-worn* and *wrist-worn* prototypes (Figure 6.2a&b) consist of a custom mount (20x20x2 mm) for the hemispherical input sensor. A band of thin Velcro allows for fast and easy affixing to the user's finger or wrist. The *pendant* contains a 3D-printed mount (30x35x2 mm), which is attached to a necklace (Figure 6.2c). Its aesthetic design was inspired by existing pendants. Future devices could be embedded in various surface materials and be offered in different sizes to fit the user's body. In all prototype mounts, the sensor surface is protruding the mount by 6 mm. The sensor is tethered either to a computer or a battery-powered Raspberry Pi 2 over USB.

ExpressSkin input can be used along with *various output devices*. This includes auditory output or visual output on existing wearables, such as smartwatches or head-mounted displays. Furthermore, auditory or haptic output could be integrated right within the input device. ExpressSkin can also be used to control mobile handheld devices, e.g. while they are put in a bag or pocket, or stationary devices, such as TV sets or gaming consoles. We use a wrist-worn 2.2" display to provide visual output in a smartwatch form factor. Alternatively, it could connect to Google Glass and Oculus Rift for visual output on a head mounted display or provide audio output on a headphone.

6.3 Interaction Techniques

In the following, we illustrate the novel interaction capabilities of ExpressSkin by presenting five interaction techniques, which leverage force input on the tiny device surface. The techniques offer support for navigation, gestures, and pointing – important classic tasks for mobile HCI that were difficult to perform with existing two-dimensional input techniques on tiny wearable devices. A set of example applications demonstrate the use of ExpressSkin in conjunction with important wearable output devices, including smartwatches, head-mounted displays, and audio feedback.

6.3.1 Fluid Pan-and-Zoom for Small Displays

Panning and zooming [7] are frequent and important interactions to navigate in information spaces, e.g. city maps, documents, or photos. The small screens of wearable devices makes them paramount interactions for wearables. Most wearable devices separate pan and zoom into consecutive actions, because they only allow for two-dimensional input. In contrast, ExpressSkin allows for continuous, precise and *simultaneous* pan and zoom, due to its three-dimensional input space. Two-dimensional shear force is used for panning. Pressing is used for zoom-in, and squeezing for zoom-out. Noteworthy, this intuitive mapping is made possible through our investigation of squeeze input, because the sensor by default did provide an opposed input to pressure. The applied forces are mapped to the speed of panning and zooming.

We implemented *one-handed smartwatch input* for navigating maps (Figure 6.1b). The ExpressSkin device is located on a finger of same hand where the watch is worn. We have empirically chosen a threshold of 1.25 N to prevent accidental zoom. The amount of force is linearly mapped to the speed of the zooming.

6.3.2 Gestures and Gesture Modes

Gestures are a fast way to enter commands on wearable devices, e.g. to accept/decline calls or to control a music player. However, the tiny wearable devices is commonly too small to support a large set of gestures. The three force input primitives of ExpressSkin allow for a *large three-dimensional gesture space*, which allows for more unique gestures and expressive mappings. To illustrate this, we present in Figure 6.8 a gesture set for common operations on smartwatches. The gestures were designed by three interaction designers to demonstrate the expressivity of multi-dimensional force input. Navigation actions are based on shear input. The additional squeeze and pressure forces help to resolve ambiguous commands, e.g. moving inside the app and between apps. Squeeze invokes navigation through apps, while pressure executes application-specific commands. The gesture set distinguishes between light pressure for selection and hard pressure for execution. Copy and paste are inspired by picking an element (squeezing) and placing it (pressing) somewhere else. Undo and redo are inspired by setting the time on a watch crown. The amount of shear circles specifies how much actions should be undone or redone. As demonstrated the gestures can combine pressure with shear and squeeze with shear. This allows for versatile mappings that can be quickly executed and easily memorized. The small movements involved support discreet gesture input. Furthermore, the gestures can be performed one-handed, when ExpressSkin is worn on the finger or is attached to a graspable object.

To further extend these 2D shear gestures with quasi-modes, we introduce *Gesture Modes*. Quasi-modes are selected by adding pressure or squeeze while performing the shear gesture. Hence, the same two-dimensional shear gesture can be mapped to different (ideally related) commands. The gestures therefore *remain simple and easy to remember* despite the larger command set. Experienced users can even change the quasi-mode *during* a continuous shear gesture by changing the amount of pressure or squeeze. This is especially useful for commands that are related and often performed in a sequential order (e.g. fast forward, skip song and skip album, see Figure 6.9c).

As an application example, we implemented an eyes-free audio player (Figure 6.9a). Shearing left or right continuously seeks backwards or forwards in a song. The amount of shear force is mapped to the speed of the seeking, allowing for fine-grained control. To seek through the list of songs in an album, the user adds a light pressure force (1 N to 2.5 N). To seek through all albums, the user presses more firmly while doing the seeking gesture (>3.5 N). Experienced users can smoothly navigate through their music: they integrate the actions of fast forwarding within a song, skipping songs and skipping albums, simply by increasing or decreasing the amount of pressure during the shear gesture (Figure 6.9c).

6.3.3 Six-Way Navigation

Mobile icons, pictures and other data is often shown in a 2D grid and clustered in albums and folders. Two-dimensional input of most wearable devices is not sufficient to browse these structures and requires additional buttons (e.g. “home”, “back”, “preview”, “open”). ExpressSkin allows for navigating up/right/down/left using shear forces *and* navigation through the hierarchical structure: Pressure enters a deeper level, squeeze returns to a higher level. Hence, it provides navigation in *six directions* on the same tiny input surface. The amount of shear force in each direction can be mapped to the navigation speed. The different force levels of pressure and squeeze allow for different commands, e.g. light pressure previews the selected item and a higher force opens it. Six-way navigation also supports precise, speed-controlled movement of an avatar through games similar to an analog stick.

We realized this interaction technique in two application examples. First, we implemented this technique for occlusion-free navigation in a photo gallery for smartwatches (Figure 6.10a). Second, we implemented a controller for Super Mario 64 on a VR headset (Figure 6.10b). Shearing moves Mario through the level with a controlled speed, light pressure (1 N to 2.5 N) makes him jump, high pressure (>2.5 N) double jump, and squeezing (>1.25 N) lets him crawl.

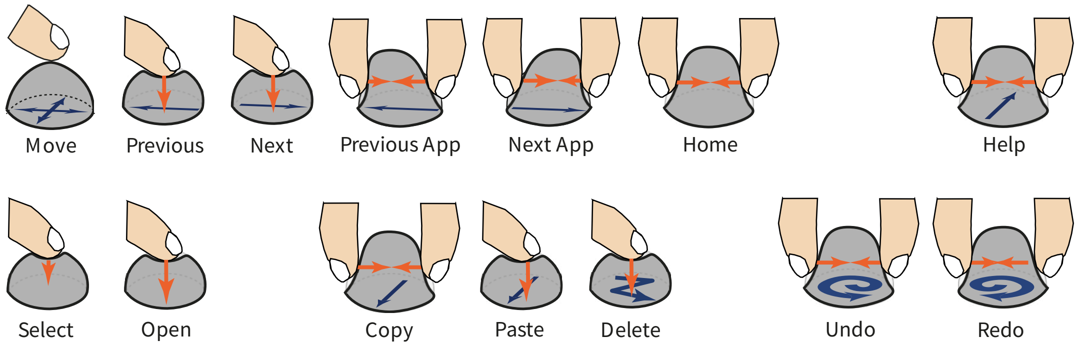

Figure 6.8: Gestures for smartwatch interactions. Pressure and squeeze forces are drawn in orange; shear forces in blue.

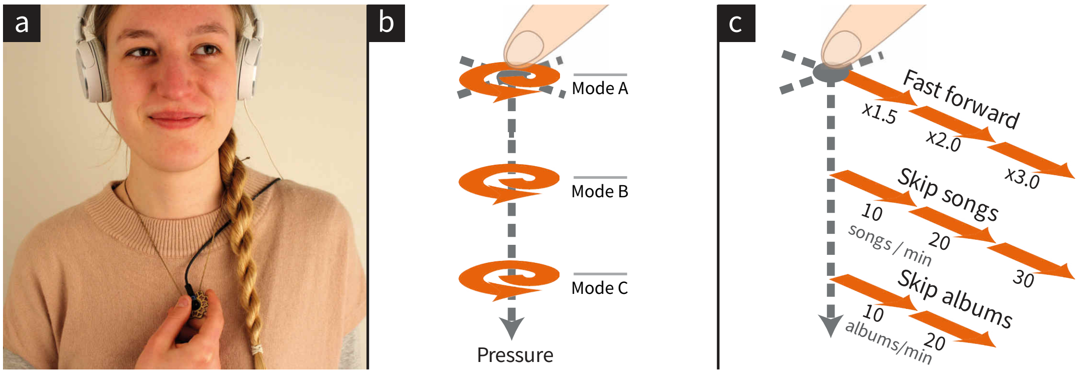

Figure 6.9: Gesture Modes increase the expressivity of gestures: (a) Controlling a music player. (b) The same shear gesture can be mapped to different commands using pressure. (c) Example mapping of continuous shear gestures for a music player.

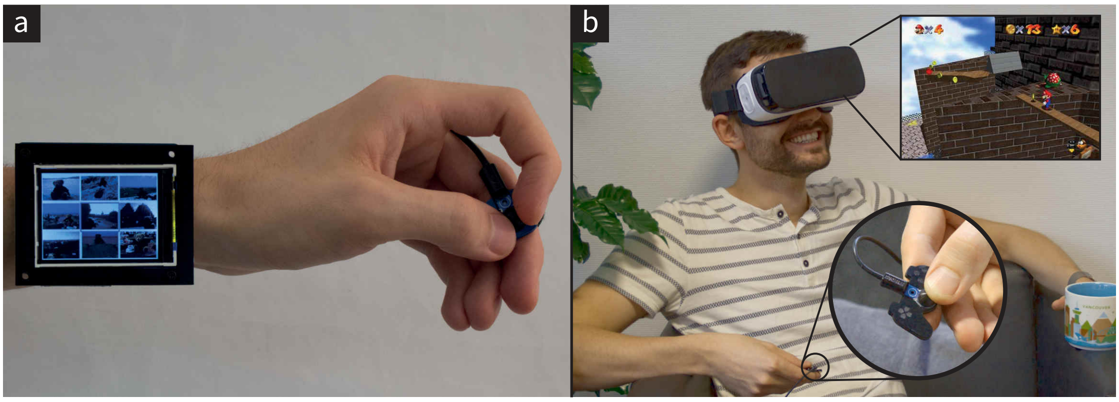

Figure 6.10: Example applications of six-way navigation: (a) occlusion-free navigation in a photo gallery for smartwatches and (b) ExpressSkin as a key-chain controller for mobile VR gaming.

6.3.4 Radial Selection & Navigation

Shear input does not only provide four directions, but allows for radial input. This interaction technique is useful for applications that only require a single degree of freedom, e.g. to set a time, a position in a progress bar, or an item in a radial menu. The shear angle chooses an item, which is selected as soon as the shear force exceeds a threshold. As for six-way navigation, squeeze and pressure allows to navigate through multiple stacked levels. For example, this can be used to offer a higher number of menu items without sacrificing fast selection.

We implemented a stacked radial menu for a messaging application with our finger-worn prototype (Figure 6.1c). It offers fast and discreet menu input for a head-mounted display while supporting a large number of menu items. Each menu level contains eight menu items. A selection is highlighted with a light shear force ($1 - 2$N) and selected with a medium force ($>$ 2N). The stacked menu levels contain standard mail options, quick-reply templates, and sharing options.

6.3.5 Force-Sensitive Pointer Input

Shear input on trackpoints has been used as a pointing input on notebooks [194]. Pointing input is useful for wearable devices, e.g. for drawings and annotations on head-mounted displays or slideshows. The form-factor of ExpressSkin allows for these scenarios using continuous, high-resolution shear input. In contrast to a trackpoint, ExpressSkin supports high-resolution pressure or squeeze input *during* the pointer movement. Hence, enabling force-sensitive pointing input. For example, the user can draw with varying stroke width by manipulating the pressure force while moving the pointer. Similar, squeeze forces allow for a force-sensitive second command, e.g. an eraser with varying diameter.

We implement an annotation application for projected presentations. Shearing moves the pointer; pressure changes the pen width and squeeze the width for the eraser. We chose a low force of $1.25N$ as required threshold for annotating and erasing.

6.4 Evaluation

To assess the feasibility and usability of the ExpressSkin input principle and of the interaction techniques that were illustrated above, we empirically investigated the following questions:

1. How performant and precise is force input on various body locations?
2. How many levels of force can be distinguished?
3. Can it be used in mobile scenarios like walking?
4. Can users combine shear with pressure or shear with squeeze in one gesture?

We evaluated the ExpressSkin prototypes in four tasks: first, we evaluated the basic performance of pressure, shear, and squeeze forces (T1+2); next, we evaluated gestures that combine shear with pressure or squeeze (T3); finally, we evaluated the combination of relative shear and absolute pressure (T4). All tasks are evaluated on three body locations, while standing and walking. The evaluation was split into two sessions to avoid fatigue effects. The average duration of session 1 was approx. 90 min and 60 min for session 2. Session 1 comprised task 1&4; session 2 comprised task 2&3. A two-month break between sessions prevented training effects.

Participants. We recruited 12 participants for session 1 (6f, mean age 25.3y) and 12 for session 2 (6f, mean age 24.8y; 8 participants from session 1). Participants received a small compensation for their participation.

Setup and apparatus. The participants were standing and walking on a treadmill (Horizon Fitness Paragon 6) to allow for a controlled movement speed. User input and target were visualized on a 24” display (1920x1200px) that was affixed in front of the treadmill with approx. 1 m distance to the user. We chose to evaluate ExpressSkin on three common locations for wearables: finger, wrist, and pendant. Participants could choose their preferred grasp for the pendant and their preferred side for the finger-worn and wrist-worn device condition to achieve optimal results for each force task. At any point during the study, participants could freely decide with which finger they operated the device. Furthermore, all input was performed without looking at the input device. The raw input from the sensor was logged for later analysis. Participants were free to take breaks at any point during the study, but none of the participants decided to do so.

6.4.1 Task 1: Performance of Shear and Pressure Input

In a target acquisition task, we investigated the basic performance and accuracy of pressure and two-dimensional shear input. Task 1 considers forces that can be performed by a single finger, i.e. pressure and shear. Participants performed the task with three devices (finger-worn device, wrist-worn device and pendant) in two activities (standing and fast walking with 4 km/h). Participants were acquiring two-dimensional shear force targets (up, left, down, right) and pressure targets. The setup is similar to prior force-studies on rigid mobile phones displays [115]. For each direction (pressure and up/left/down/right shear), we evaluate six targets. The target distances cover low (1.25 N), medium (2.75 N), and high forces (4.25 N). As target widths we chose 1.5 N (representing three targets on each direction) and 0.75 N (representing six targets on each direction). They represent easy (1.5 N) and challenging tasks (0.75 N) for wearable devices.

Participants were asked to acquire the targets as fast and precisely as possible. The target was visually highlighted as soon as it was acquired. After a dwell time of 1 s, the target was successfully selected. Then, after the user had reset the input (force less than 0.2 N), the next target was activated. Each target was repeated three times.

This setup resulted in *3 (device conditions) x 2 (activities) x 5 (directions) x 3 (distances) x 2 (widths) x 3 (repetitions) x 12 (participants) = 6,480 trials.*

6.4.2 Task 2: Performance of Squeeze Input

Task 2 evaluates the basic performance and accuracy of squeeze forces. Compared to T1, this type of input requires at least two fingers for the interaction. We changed the target space to better reflect the sensitivity range of our force sensor. As squeeze force levels we used low (2.3 N), medium (3.3 N) and high forces (4.4 N). The target widths were adjusted to reflect the smaller target space (1 N and 0.5 N). Otherwise, the same setup and conditions were used as in T1.

This setup resulted in *3 (device conditions) x 2 (activities) x 3 (distances) x 2 (widths) x 3 (repetitions) x 12 (participants) = 1,296 trials.*

6.4.3 Task 3: Shear+Pressure and Shear+Squeeze Gestures

Task 3 investigates the basic performance and accuracy of gestures that combine pressure or squeeze forces with shear forces, similar to the gestures in Figure 6.8. The setup was the same as in T1, but the participant needed to combine two force primitives at the same time and hold them for a dwell time of 1 s. Participants performed the task with the three demonstrator devices in two activities (standing and fast walking with 4 km/h), i.e. in six conditions. For squeeze and pressure forces, the target distances were the same forces as in T1 and T2 with the larger target width. For shear forces, the targets required a medium force (2.75 N) with 1.5 N target width in one of the four dimensions. Each target was repeated three times.

This setup resulted in *3 (device conditions) x 2 (activities) x 4 (directions) x [3 (squeeze distances) + 3 (pressure distances)] x 3 (repetitions) x 12 (participants) = 5,184 trials.*

6.4.4 Task 4: Pressure-Sensitive Relative Shear Forces

This task studies relative movement using shear forces while holding a pressure level, e.g. as required for force-sensitive movements. Participants were asked to hold the pressure in an absolute force range and use shear to navigate a target to the center of the screen. The target could only be moved when the participant applied a pressure within the specified range. The pressure ranges were low (0.5 N to 2 N), medium (2 N to 3.5 N), or high force (3.5 N to 5 N). The targets to navigate using shear input had a distance of 500 px from the center and were distributed in eight directions around the center ($\angle 0, 45, 90, \ldots, 315$). The 2D shear input moved the target with a speed of $350 Px/Ns$. In an informal pre-study with 5 users we identified this speed as a good balance between speed and control. The target could not leave the visible display area. As in T1, Participants performed the task with the three demonstrator devices in two activities (standing and fast walking with 4 km/h), i.e. in six conditions. For each target the user made three repetitions.

This setup resulted in *3 (device condition) x 2 (activity) x 3 (pressure ranges) x 8 (shear directions) x 3 (repetitions) x 12 (participants) = 5,184 trials.*

In each session the order of tasks was counterbalanced. Within each task, the order of device conditions was counterbalanced and all targets were randomized to avoid bias. The order of activities (standing and walking) was counterbalanced between participants to avoid learning effects, but constant for each participant to avoid fatigue. In all tasks, participants had unrestricted practice time before each test condition for making themselves familiar with the device and the activity, until they felt comfortable with the task (on average 3 minutes per task).

6.4.5 Results

Our analysis focuses on task completion time and errors. We chose the task completion time as the most commonly used performance measure. It captures a set of realistic factors: complexity of the primary task, walking, and precise target acquisition (time penalty from under- and overshooting). Moreover, it is better-suited for statistical analysis compared to the low number of error trials. All data is reported without any outlier filtering. All trials except one could be successfully accomplished by all participants. The exception was for the wrist-worn device while walking when one participant wanted to skip a difficult target; we removed this trial from the dataset.

T1. The performance results of T1 can be found in Figure 6.11a+b and d+e. In the *standing* condition, all tasks had average tasks completion time of less than 2.2 s for pressure and 2.7 s for shear forces, including the 1 s dwell time. The wrist-worn device was the fastest device with an average task completion time of 1.615 s. For the ring it took 1.701 s, and for the pendant 1.721 s. These small differences were not statistically significant.

A paired t-test shows significant differences between the task completion times of standing and walking ($t(3239) = 12.16, p < 0.001$). While *walking*, the task completion time increased on average by 20.6%. This increase was surprisingly small for the finger-worn device (8.1% longer) and the pendant (7.8% longer). In contrast, the increase amounted to 46% for the wrist-worn device. It is noteworthy that the wrist-worn device had the best performance of all three devices in the standing condition, while it had the lowest performance in the walking condition. An ANOVA identified significant main effects between the devices ($F(5, 66) = 10.61, p < 0.001$). Bonferroni corrected post-hoc tests found significant differences between the wrist-worn device while walking and all other walking conditions.

We calculated the number of errors, i.e. how often participants dwelled for 1 s on the wrong target. The error rate was 0.3% while standing and 0.5% while walking.

T2. The performance results are depicted in Figure 6.11c+f. The average task times were below 2.5 s in the *standing* condition and below 2.9 s in the walking condition. A paired t-test shows significant differences between the task completion times of standing and walking ($t(647) = -4.5946, p < 0.001$). While walking, the task completion time increased on average by 9.8%. The error rate was 0.15% for the standing and 0% for the walking conditions.

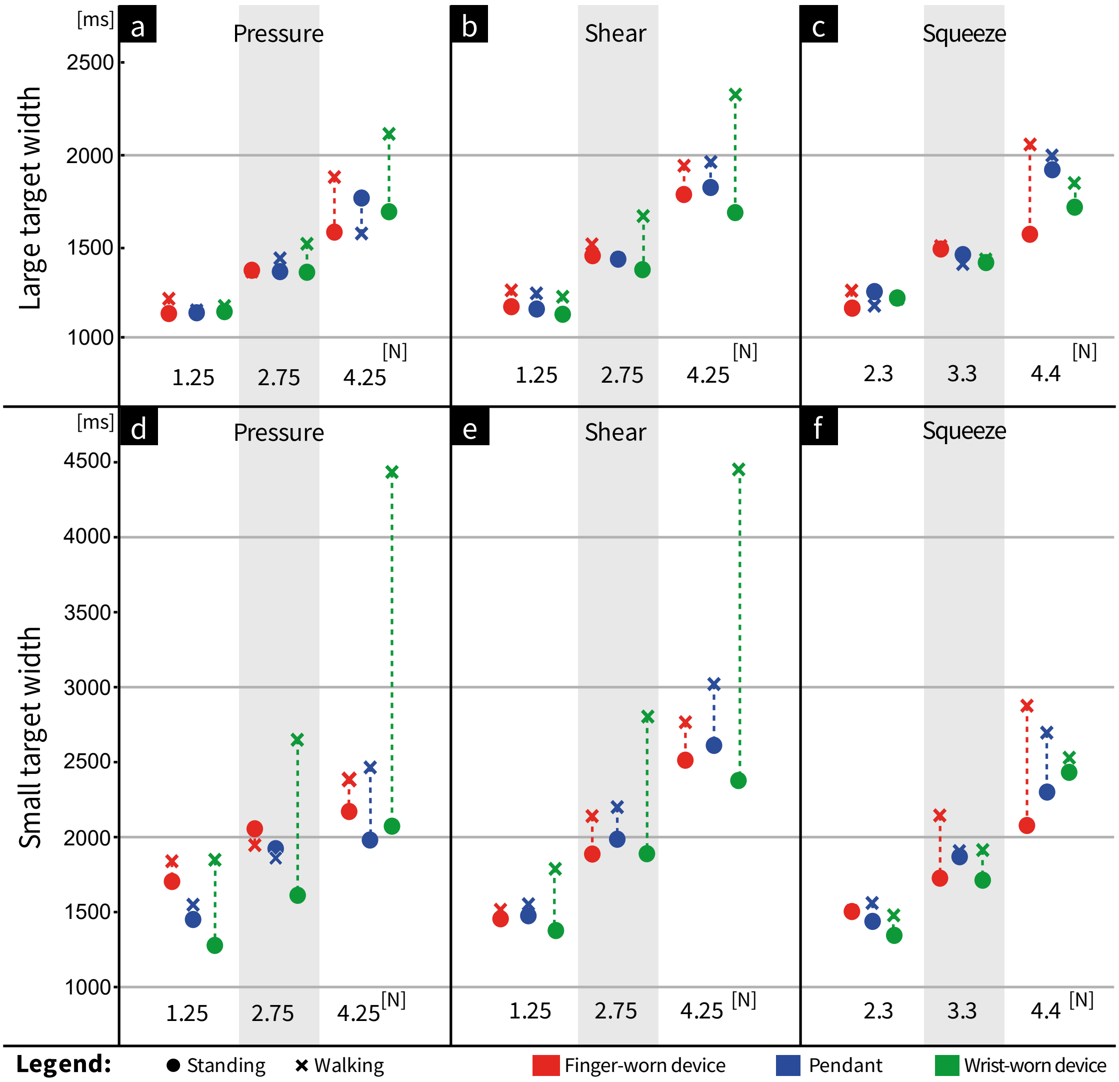

Figure 6.11: Results of controlled experiments on wearable force input: Average task completion times from T1 and T2 for pressure, shear, and squeeze targets. All times reported in include a 1 s dwell time.

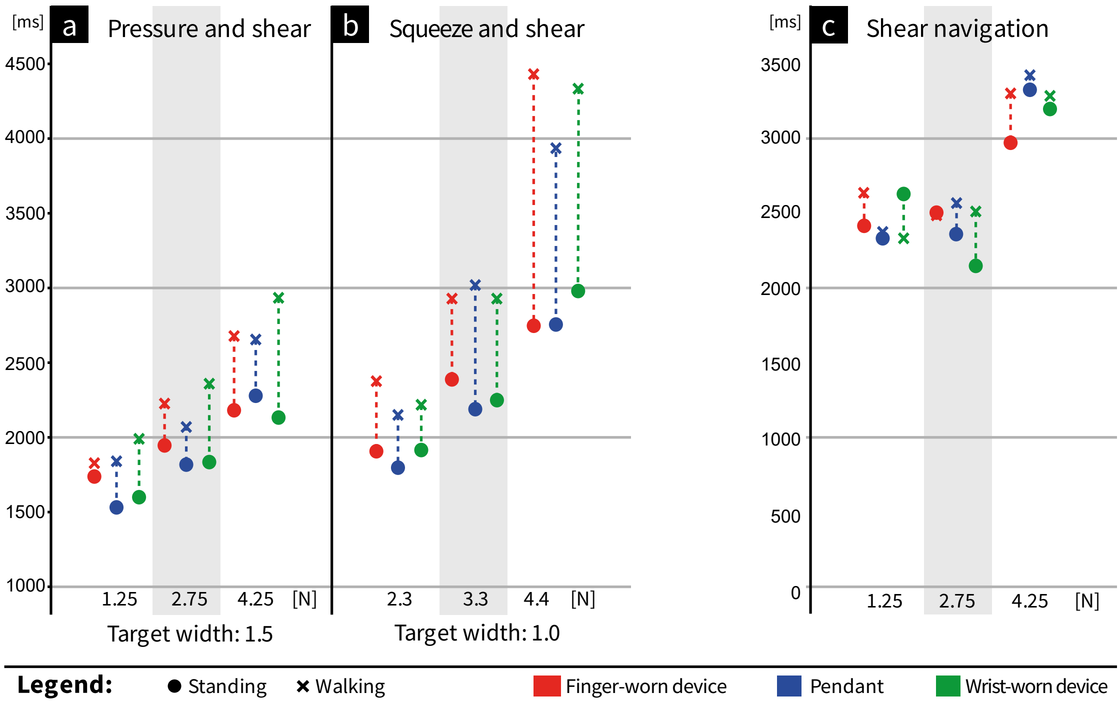

Figure 6.12: Average task completion times in T3: (a) Combined pressure and shear force targets and (b) combined squeeze and shear force targets. The times reported in (a&b) include a 1 s dwell time. (c) Average task completion times of T4.

T3. All *shear+pressure* combinations were acquired in less than 2.2 s in the standing condition. The average task time was 1.9 s and the error rate 3.9%. In the walking condition, the task completion time increased by 20.6%. A paired t-test shows significant differences between standing and walking condition ($t(1295) = -9.8532, p < 0.001$).

All *shear+squeeze* combinations were acquired in less than 2.9 s in the standing condition. The average task time was 2.3 s and the error rate 5.1%. In the walking condition, the task completion time increased by 35.2%. A paired t-test shows significant differences between standing and walking condition ($t(1295) = -11.699, p < 0.001$).

These results show that pressure and squeeze forces can be combined with simultaneous two-dimensional shear input. For approximately the same index of difficulties, shear+pressure and shear+squeeze perform with similar mean times.

T4. The performance results of T4 are depicted in Figure 6.12c. The mean task completion time was 2.71 s in the standing condition and 2.82 s (+4.1%) in the walking condition. The devices show similar average completion times. We did not find a statistically significant difference between the standing and walking conditions, nor between the three devices.

We compared task completion time for the three different pressure ranges. The mean times were similar for low force (2.51 s) and medium force (2.49 s). It was considerably higher for large force (3.31 s). An ANOVA identified significant main effects between pressure range ($F(1, 11) = 10.961, p < 0.05$). Bonferroni corrected post-hoc tests found significant differences between the highest pressure-range and the two remaining ones. This indicates that combining shear with high levels of pressure is significantly more challenging for the user.

These results show that all devices allow for two-dimensional shear input while the participant is holding a pressure in one of three levels. Despite the complex combinatory tasks, participants achieved high input performance. The increased task completion time for high pressure inputs should be considered when a fast execution is required.

Input Strategies. We observed different input strategies during the tasks. For input on the wrist, 75% of participants used the index finger and 25% the thumb. For the pendant, 83% used the thumb and 17% the index finger. squeeze input was performed with both the thumb and the index finger by all participants. We also observed different grasps of the pendant: 6 participants (50%) used it for one-handed input, similar to the finger-worn device; 3 participants (25%), used two hands; another 3 participants (25%) switched between one- and two-handed usage during pressure and shear forces. For squeeze input, eleven participants (92%) interacted on the pendant two-handed. One participant (8%) switched hands during the experiment. For the finger-worn device, all participant interacted one-handed on their dominant-hand for shear and pressure tasks. For squeeze forces, 3 participants (25%) attached the device to their middle finger. One used one-handed input with thumb and index finger for all targets, the other two switched between one and two-handed input. One participant commented: "I have to take the other hand for the smallest targets [highest force], because I have not enough strength" [P12]. The other 9 participants (75%) attached the device to their non-dominant hand and interacted with their dominant hand.

6.5 Discussion and Design Implications

Based on the evaluation results and on lessons we have learnt during the iterative design and prototyping, we derive design implications for ExpressSkin. We discuss the influence of form factor and body location, derive implications for our interaction techniques and detail on the comfort of force input on wearable devices.

6.5.1 Form Factor and Locations

The findings of the empirical study demonstrate that force input is fast and precise for all devices in the standing condition. In the walking condition, we found significant differences between the devices. While the ring and pendant only had a small increase in their average task completion time (7.1% and 8.1%), the average task completion time of the bracelet increased by 20.6%. This shows that form factor and body location have a major influence on the performance of force input. In the following, we will discuss the results of the study and derive design implications for each location:

Finger-worn device. Input on the finger-worn device showed a good performance, combining low task completion times and low number of crossings, for both standing and walking conditions. This makes it an appropriate candidate for interactions that are likely to happen during movement, e.g. on fitness devices. The finger-worn device can be used for one or two-handed interactions. All participants chose to use the ring as a one-handed input device for shear and pressure input; for squeeze input, one forth of the participants opted for one-handed input, squeezing the sensor with the thumb and the middle finger. Hence, all force primitives can be performed in one-handed input, but the majority of participants used the other hand for squeezing. Therefore, interaction designers should carefully chose the required amount of squeeze force for one-handed scenarios. Last but not least, the finger-worn device was rated as the favorite device by the majority of participants.

Wrist-worn device. The wrist turned out to be the best evaluated locations for force input when the user was standing. This makes it a great addition to smartwatches. Added onto the bezel or onto the bracelet of a smartwatch, ExpressSkin enables occlusion-free input. However, we identified a significant performance drop for difficult targets while the user was walking. This might relate to the fact that the input location requires the user to bring together both hands in front of the body; this could conflict with naturally swinging the arms as it happens while walking. As a remedy for improved wrist-input while walking, we recommend that the interface automatically adapts to the activity level: it should switch to an easier interface when walking is detected, e.g. by using an accelerometer. For example, a menu can show only the most frequently used items during walking. If this is not an option, an additional input sensor for one-handed interaction (e.g. on the finger) could be used to interact with the smartwatch.

Pendant. The performance of input on the pendant was similar to the performance of the finger-worn device. Hence, it can be characterized as a good device form factor both for standing and walking. During the study, the pendant was grasped in various ways: while one-handed input was most frequent, a considerable number of participants grasped it with the non-dominant hand and operated it with the index finger or thumb of the dominant hand. Therefore, the device needs to be comfortable and easy to hold in these grasp styles.

Input while Walking. Engineers and designers should carefully consider in which mobile activities the device is to be used. For devices that are designed for use while walking, one-handed interactions should be preferred to avoid conflicting with the natural movement of the arm. They can be either attached to the finger or temporarily grabbed for input, e.g. as we have realized with the pendant device. These forms of input have shown to offer an input performance while walking that is almost as high as in an immobile setup. Our study has not studied interaction while running; this remains to be investigated in future work.

6.5.2 Interaction Techniques

The four tasks of our user study evaluate single-dimensional and multi-dimensional force input. Results from Task 1 and 2 showed that pressure, shear, and squeeze forces are expressive input dimensions, allowing users to reliably distinguish and hold at least six different levels. The results from Task 3 show that participants can combine and hold a low, medium and high pressure or squeeze force simultaneously with a two-dimensional shear force. In addition, Task 4 shows that participants can use shear forces for relative movements while holding one of three pressure ranges. Based on these findings, we derive design implications for our force-based interaction techniques:

Fluid Pan and Zoom. Continuous panning and zooming can be performed precisely with six speed levels. Task 3 combined panning (shear) with zoom input (pressure or squeeze). This shows that the user can zoom-in and zoom-out in three different speeds *while* panning the map.

Gestures and Gesture Modes. Our studies show that ExpressSkin allows for linear gestures with six different force-levels for pressure (T1), 2D shear (T1), and squeeze (T2) input. They also support gestures inside the rich three-dimensional input space by combining 2D shear input with either pressure or squeeze (T3).

Gesture Modes can have at least six different modes, three for pressure and three for squeeze. Task 3 shows that users can perform two-dimensional shear input while holding a pressure or shear force in one of three force levels. These findings directly translate to performing a linear shear gesture in a specific mode, e.g. in our music player example. The most frequent commands should be mapped to low and medium pressure modes. Less frequent commands can be mapped to input with a higher task completion time, e.g. the modes with strong pressure or strong squeeze input.

Six-Way Navigation. The results of task 1 and 2 show that ExpressSkin allows for interaction in all six directions. Each of the six direction allowed for six different force targets. These can be either mapped to six speed levels or to six different commands (e.g. select, preview, open).

Radial Selection and Navigation. The results of task 4 suggest that radial selection is possible for eight directions. This allows for radial menus with eight menu items. Tasks 1 & 2 show that pressure and squeeze allow for navigating though multiple stacked levels. Finding the upper limit of radial items is yet unknown and remains for future work.

Force-Sensitive Pointer Input. Task 3 shows that ExpressSkin allows for combining shear with pressure or squeeze force input. Task 4 shows that continuous pointer movement is possible in eight directions while continuously holding a constant pressure level. Common pressure input should map to low and medium forces, because higher pressure force requires more time for task completion. squeeze force input can be mapped to a secondary command. It shows a similar performance for similar targets when combined with shear input (task 3).

6.6 Limitations

We opted for a controlled study to analyse and understand the novel characteristics of ExpressSkin. The study gives first insights into force input in mobile activities: Our analysis discovered significant differences in performance between the devices while walking. Furthermore, it showed that participants prefer different attachments and use different input strategies. As a next step, future work could build upon these results and analyze the performance of ExpressSkin in field studies. For example, by comparing two-handed and one-handed input with varying walking speeds and while running.

Our evaluation focused on input performance and does not intend to make claims about output. We opted for a neutral device configuration to bias the input task as little as possible: a stationary display is always well visible, independently of the user's hand and arm pose. A wearable display might have some effect on task performance, as it might require the user to adopt a slightly different posture for observing visual output. Due to our focus on input, we did not consider haptic output and stiffness changes, e.g. achieved through pneumatic jamming [38] or programmable gel [144].

Finally, our ExpressSkin prototypes all have a hemispherical shape. This shape allows the user to use taction for finding the center. It affords interaction in all directions. Other shapes could create different affordances, e.g. to guide the finger in certain directions. The grip on the device can be enhanced with a rough surface structure. This improves interaction with wet or sweaty fingers that are likely in outdoor and fitness scenarios. The sensor we have used for our prototypes is protruding by a few millimeter and is hemispherical. Advances in sensors make it very likely that in the future, wearable force sensors can be realized in a fully flat form factor [180, 230]. It will have to be investigated how such a change in form factor affects interaction performance.

6.7 Conclusion

This chapter investigated expressive interaction techniques for on-skin interaction. We contributed ExpressSkin, soft input surfaces for continuous and high-resolution force input. They sense pressure, shear, and squeeze forces to enable expressive on-body interactions. We demonstrate the versatility of ExpressSkin devices with three demonstrators: A finger-worn and a wrist-worn device, inspired by the prior locations for skin-worn electronics, and a graspable pendant. We demonstrate its expressive input capabilities with five force-based interaction techniques. They enable fluid interaction in a large input space by combining multiple dimensions of forces, despite the small device size. By contributing empirical findings, we showed that force-input allows for fast and precise input on many body locations, in both standing and walking conditions.

Taken together, this chapter studied expressive force-based interactions on soft, skin-worn surfaces. The chapter is inspired by our findings from section 2.3, which propose force-based interaction for on-skin input. The input capabilities exceed those of the highly conformal input surfaces in chapter 4 and 5. Therefore, the contributions of this chapter expand the interaction space of on-skin devices to expressive interaction techniques based on high-resolution and multi-dimensional force input. The proposed interaction techniques can either be used on small skin-worn devices or integrated into large, conformal on-skin sensors, e.g. iSkin (Chapter 4).

7 | Conclusions

On-skin interaction has many benefits for mobile interaction: Skin provides a large input surface that is fast to access. Proprioception and tactile receptors help to locate the interaction surface and give precise tactile feedback about the interaction. Moreover, interactive elements on the finger allow for single-handed interactions. Prior research showed that touch on the body is a promising domain for mobile computing and investigated novel on-skin sensing technologies. However, they mostly transferred tap and slide gestures from handheld mobile devices and have not been used on challenging body locations.

The goal of this thesis was to advance on-skin interactions towards expressive touch input on various body locations. Based on the findings of an elicitation study, we aimed to develop technical enablers for on-skin interfaces. Our technical enablers increased the support of possible body locations for on-skin input and enabled interactions on challenging body geometries, e.g. highly curved body parts, narrow microstructures, and elastic locations. Moreover, they offer richer on-skin interactions by sensing multi-touch *and* skin-specific modalities, e.g. pressure, shear, and squeeze input. This opens a novel interaction space for on-skin interaction. We investigated this space by contributing expressive interaction techniques and by studying their performance on the body.

This final chapter summarizes the main contributions of this thesis (Section 7.1) and identifies directions for future work (Section 7.2).

7.1 Summary

This thesis advances the field of on-skin interactions. In particular, it advances the field in the following points:

Understanding of On-Skin Input

On-skin interfaces are a novel domain in human–computer interaction. This thesis provided a user-centric understanding of on-skin input by conducting an elicitation study. The findings of the study contributed an understanding of the gestures, input modalities, and locations participants use for on-skin interaction. We found that skin has a dual-character: On the one hand, traditional multi-touch gestures transfer from rigid and flat multi-touch surfaces to the skin. On the other hand, novel skin-specific modalities were used to increase the expressivity of the interaction. The study also contributed an understanding of the mental models of participants. For example, our findings showed that participants deliberately used uncomfortable input modalities and that skin-specific modalities were inspired by interpersonal communication and the physical affordances of skin. In addition, various locations on the body were used to spatially distribute the interactions. The findings contrast prior on-skin interfaces, which focused on input areas with low curvatures, e.g. the forearm or the palm, and on tapping and sliding gestures. Our work shows that skin is more than a rigid, uniform input surface and that the unique skin characteristics could allow for expressive mobile interaction.

As our findings show that modalities beyond touch contact allow for more expressive interactions, this thesis also contributes empirical findings on force input (see Section 6.4). We show that force-based input allows for fast and precise on-skin interactions. This understanding is an important step to allow for more expressive touch interactions on skin-worn devices. Our findings detailed on the performance of shear, pressure, and squeeze input on three locations in standing and walking condition. They showed that force-based input is fast, precise, and allows for six force levels in each direction. Each of these levels can be reliable distinguished and held. Furthermore, our findings showed that pressure and shear, as well as, squeeze and shear forces can be combined for fluid and multi-dimensional input.

Input on Challenging Body Locations

Prior on-skin technologies were limited to slighly curved input locations. In this thesis we advance on-skin interaction towards challenging body locations by contributing novel skin-worn devices to enable interactions on various body locations and by contributing interaction on body landmarks.

We enabled interactions on various body locations by contributing two *technical enablers*, iSkin (Chapter 4) and SkinMarks (Chapter 5). Our technical enablers support highly curved body areas such as the finger, narrow body landmarks such as flexure lines, and areas with highly defomable skin. They can be designed and fabricated directly by researchers in human–computer interaction to ease and speed up further investigations into on-skin interactions. The required equipment is either already available in fabrication labs (lasercutter) or cheap to acquire (screenprinting). They are based on digital designs to ease the creation of novel sensors using existing design workflows and tools. This also allows for customization of the sensor's shape and size and supports personalization for the user's body. The manual fabrication steps are easy to learn and master for researchers and students. This allows for rapid prototyping, because each iteration only requires a few hours. We present prototypes that demonstrate the possibilities of our technical enablers on various body locations (see Figure 7.1).

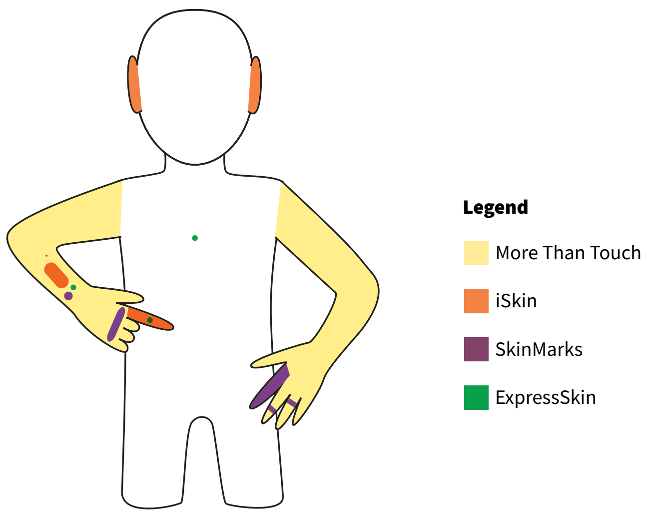

Figure 7.1: Investigated body locations

Skin contains various types of landmarks which are distinct from their surroundings and offer tactile and visual cues for interaction. These cues can provide benefits for on-skin interaction: they help in localizing interactive elements, can guide touch input on the skin, and can help in memorization and recall of interactive elements. Prior research in human–computer interaction briefly explored the potential of such landmarks, e.g. [58, 59], but lacked technical enablers to investigate interactions on these landmarks. With SkinMarks (Chapter 5), we contributed technical enablers for these interactions. We defined *body landmarks* as skin areas that visually and tactually differ from their surrounding and can support and ease on-skin input. We identified five types of body landmarks for on-skin interactions: skeletal landmarks, skin microstructure landmarks, elastic landmarks, visual skin landmarks, and accessory landmarks. We contributed and demonstrated six novel interaction techniques that use the benefits of body landmarks for on-skin interactions (see Section 5.3). They expand the on-skin interaction space towards more detailed interaction on challenging body areas.

Expressive Touch-based Interactions

The findings of our elicitation study show that people use more expressive forms of touch input. Instead of only relying on the touch location, they use variations in the contact size and excerted forces. This thesis enabled five of the eight modalities observed during the study (see Table 7.1). In this thesis, we investigated touch, pressure, grab, squeeze, and shear interactions. We did not investigate pull, scratch, and twist input, because they ranked lowest in our perceived ease and comfort ratings.

First, we enabled the three most used input modalities observed in our study: touch, pressure, and grab input. We demonstrate that accurate sensing of these modalities is possible with thin and stretchable skin-worn sensors (iSkin, Chapter 4). Our sensor is

	Touch	Pressure	Grab	Twist	Scratch	Pull	Squeeze	Shear
iSkin	✓	✓ (2 levels)	✓					
SkinMarks	✓		✓				✓	
ExpressSkin		✓					✓	✓

Table 7.1: Enabled input modalities

capable of sensing precise touch-down and touch-up events of one or multiple fingers. A sensor can contain multiple touch-sensitive electrodes that form more complex widgets, such as sliders and click wheels. Multiple electrodes also allow to sense a rough contact size of the interaction. This allows to distinguish the touch of a fingertip from the grab of a hand. Beyond conventional touch input, iSkin distinguishes two-levels of pressure. The pressure can be modulated during a touch, without lifting the finger.

Second, SkinMarks investigated touch, squeeze, and bend sensing on highly conformal skin-worn devices (Chapter 5). This demonstrates that thin and stretchable skin-worn devices are able to sense lateral squeeze input. Although SkinMarks cannot measure the excerted forces yet, our findings opens a promising path for future research that could enable high-resolution input on highly conformal skin-worn devices. Moreover, SkinMarks allowed us to investigate pose-based interaction. These interactions increase the input expressivity by changing the posture of the skin surface. For example, interfaces can distinguish between touching a straight or a bent finger to invoke different actions. Furthermore, SkinMarks enabled input surfaces with co-located visual output using skin-worn touch-sensitive displays.

Finally, we contributed interaction techniques that are based on force-based input modalities: pressure, shear, and squeeze. In Chapter 6 (ExpressSkin), we demonstrate sensing of continuous and high-resolution force input on soft skin-worn devices. We implemented five expressive interaction techniques for force-sensitive input devices. The interaction techniques enabled challenging mobile interactions: fluid pan and zoom, gesture input, six-way navigation, menuing and navigation, and force-sensitive pointing. We demonstrated the capabilities of such input for stand-alone input devices and in combination with various wearable output devices, e.g. smartwatches, head-mounted displays, and headsets.

Taken together, these contributions advance on-skin interactions towards expressive interactions on various body locations.

7.2 Directions for Future Work

In this final section, we will point out directions for future research. We will discuss possible advances in the input and output capabilities of skin-worn devices and describe open questions that should be investigated in empirical studies.

High-Resolution Input

In this thesis, we investigated multi-touch and skin-specific input modalities. We presented technical enablers with low-resolution input (iSkin & SkinMarks) and explore interactions on small, high-resolution surfaces (ExpressSkin). ExpressSkin can be embedded into larger skin-worn devices to enable (multiple) force-sensitive buttons. However, we believe that increasing the overall resolution of multi-touch and skin-specific modalities could further increase the expressiveness of on-skin input.

The resolution of *multi-touch input* can be increased using sensor matrices and by interpolating between their values. This thesis demonstrated that both, sensor matrices and interpolation, is possible on skin-worn devices. We presented a sensor matrix in our keyboard prototype (Section 4.4) and interpolated between two electrodes to enable sliding (Section 5.2.3). Future work could build upon these technologies to fabricate and investigate high-resolution touch areas on skin-worn devices. This would allow for the multi-touch gestures used in our elicitation study (Chapter 2.3), e.g. pinch-to-zoom, cursor control, and drawing.

Chapter 6 demonstrated that high-resolution force-based input enables expressive interactions in a rich multi-dimensional input space. Future work should investigate high-resolution sensing of *force-based modalities* inside thin and stretchable sensors. On one hand, it could eliminate the need to interact at one particular position, which would improve accessibility and eyes-free interactions. On the other hand, it could enrich the interaction space by taking the contact location into account. This could allow for on-skin interactions that combine touch and force input, similar to prior research on handheld devices [64]. Beyond force input, our technical enablers support binary bend sensing, e.g. detect if a finger is bent or not. Increasing the resolution of bend sensing could increase the expressiveness of pose-based interactions and enable novel application possibilities for interactive skin, e.g. hand and face tracking.

Other Input Modalities

This thesis investigated five of the eight observed input modalities (see Table 7.1). Future research should enable and investigate interactions with the three remaining modalities: pull, scratch, and twist input.

Pull input is very similar to squeeze input. Both require two fingers to excert forces on the skin between the fingers. However, there is a different mental model between pull and squeeze: pull lifts the skin, while squeeze only compresses the skin. Noteworthy, our sensor prototypes are currently unable to distinguish between both input modalities. Future sensors could add support for pull as a separate input modality by measuring the direction of the force excerted by each finger.

Scratch input is performed by fast movements of the fingernails on the surface. The rapid movements of scratch input could be sensed with high-resolution, multi-touch sensors. However, our findings show that our participants did not feel comfortable using scratch input for mobile interactions, because they found that it was a social unacceptable input modality. Hence, future work should investigate the benefits and drawbacks of scratch input for mobile interaction and consider other motion-based input techniques as a replacement for scratch input.

Twist input was the fourth most used input modality (4.4%). Twist interactions could further extend our force-based interaction techniques. Twists are similar to combinations of squeeze and shear input. However, during a twist, each finger creates a lateral force in a different direction. With our current sensors, twist input cannot be distinguished from squeeze input. One solution to this issue would be to increase the sensor's spatial resolution to sense the individual force directions of each finger.

Unintentional Input

Unintentional input is one of the open issues in on-body interaction. We expect that unintentional input mostly depends on the body location and orientation of the interactive elements. For example, interactive elements worn on the finger pointing towards the hand might conflict with grasp actions, while showing towards the back of the hand does not. From our experience we noticed that protruding body landmarks and the inner areas of the palm are more susceptible to unintentional input when compared to other locations. Body landmarks located at locations that retract, such as the area in-between the knuckles, seem promising to reduce the likelihood of unintentional input. Designers and engineers need to carefully select the location where interactive skin should be worn.

Future work should investigate when and how in daily use skin-worn devices are in contact with other body parts or objects. This will allow for fine-tuning the sensor's sensitivity by tuning sensing parameters. 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 to identify and to remove unintended contacts. Another approach consists of using expressive gestures that are more robust by design, such as the presented directional toggle gesture or squeeze-based input (both in Chapter 5).

Output Capabilities

Although the primary focus of this thesis was on input technology, we show that interactive skin can integrate visual output (Chapter 5). Our electroluminescent displays support custom-shapes, sizes, and different colors. However, their visual content needs to be known at the time of their fabrication. Future skin-worn devices could make use of dynamic output using matrix display screens. To allow for such display types, the resolution of visual on-skin output needs to be increased. Promising directions are tiny interconnected LEDs [163, 193] and stretchable PLEDs [239]. However, these approaches currently require more sophisticated fabrication approaches and are not usable for rapid prototyping of on-skin devices.

Haptic output is a further very promising output channel for skin-worn devices. Due to its proximity to the skin, it could allow for highly localized and subtle haptic feedback, e.g. through vibration or temperature changes.

Automate Design and Fabrication

The technical enablers proposed in this thesis currently involve manual design and fabrication steps. Although the creation of our technical enablers is fast enough to allow for rapid prototyping, future work could improve the fabrication by automating the design and fabrication processes. In the *design process*, automation could allow for automatic routing of wires and assist the designer to avoid bottlenecks that increase the resistance of the connections. They could also improve the mapping of sensor elements to the skin by reducing the amount of necessary measurements. For example, they could enable the user to scan his body geometry or support the design of electronics directly on the skin. In the *fabrication process*, on-skin electronics could be fabricated using ink-jet or aerosol printing. These techniques would allow for custom-shaped printing of functional inks on temporary tattoo paper. This would not only speed up the prototyping, but help spreading the technology, e.g. for use in schools or makerspaces. In addition, consumer-friendly printers would allow for on-skin electronics that are printed on demand in the home of the consumers.

Comfort and Tactile Feedback

Although our results are promising in terms of comfort, we see many possibilities for further investigations. The skin-worn surface are very thin and stretchable. Hence, it is highly conformal to the skin. From our experience, SkinMarks (Chapter 5) is comfortable to wear and becomes unnoticeable when worn over longer durations. However, more research is required to evaluate the wearability of skin-worn devices in everyday scenarios, especially those involving high activity levels and many dynamic movements such as sports.

In addition, the comfort of force-based interactions should be considered. All our prototypes use only small forces during interactions. These forces are perceived by the interacting finger and by the body at the location of the input surface. Therefore, force-sensitive elements on the skin should avoid highly pressure-sensitive body parts, e.g. the top of veins. Future research should investigate the optimal force range that is comfortable to use on skin-worn devices. As some participants deliberately used uncomfortable input for important commands and to avoid accidental input (Section 2.3), this might be an interesting domain for further research. Further investigations should be conducted to better understand the benefits and risks of uncomfortable interactions for mobile computing.

Future work should consider a more thorough exploration of the impact of skin overlays on tactile feedback. Our technical enablers allow for very thin skin-worn surfaces minimizes the impact of the overlay. In addition, the prototypes adapt to microstructures on the skin, e.g. flexure lines and wrinkles, and pass their tactile cues to the user. However, an interacting finger is still able to feel a difference in tactile texture, between the overlay and direct contact with skin. Future skin-worn devices could either try to mimic the tactile properties of skin to become indistinguishable or use the tactile differences for tactile feedback.

Connection and Mobility

In this thesis, we investigated skin-worn devices from an interaction perspective and focused our efforts on novel input surfaces. To ease prototyping, our prototypes are tethered to a computer, which processes the input. As a first step towards a fully mobile setup, miniaturized rigid microcontrollers (e.g. Intel Curie) could be combined with flexible batteries. The rigid electronics could be integrated into a small rigid pin that would lead to less flexible areas inside the skin-worn surface. They could allow for communication with other mobile and wearable devices using wireless networks, e.g. Bluetooth, WiFi, and ZigBee.

Application Fields

The application examples of this thesis focused on mobile interactions for consumer electronics. We addressed common tasks for mobile human–computer interaction, e.g. accepting and declining calls, controlling the music, and navigation in maps and menus. We chose this application domain, because it provides easy and understandable examples. However, the presented technical enablers and interaction techniques are not limited to this application domain.

Future research should investigate the use of skin-worn devices in other application domains. Especially those fields that involve highly mobile interactions and challenging input tasks. Promising application domains for future research include, but are not limited to: sports and fitness to enable fast and single-handed interactions, medical devices that require always-available user input, mobile communication and notifications, and wearable terminals for logistics and warehousing.

The interaction capabilities of current wearable computing devices are too limited for many of these application domains. We believe on-skin interaction plays a critical role to expand the interactive capabilities of wearable computing. This thesis contributed to the understanding of on-skin interaction, enabled interactions on challenging input locations, and presented novel interaction techniques for mobile computing. We envision these steps to advance wearable computing towards expressive on-skin interactions and highly mobile computing.

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