Human–Computer Interaction on the Skin

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The skin offers exciting possibilities for human–computer interaction by enabling new types of input and feedback. We survey 42 research papers on interfaces that allow users to give input on their skin. Skin-based interfaces have developed rapidly over the past 8 years but most work consists of individual prototypes, with limited overview of possibilities or identification of research directions. The purpose of this article is to synthesize what skin input is, which technologies can sense input on the skin, and how to give feedback to the user. We discuss challenges for research in each of these areas.

CCS Concepts: • **Human-centered computing** → **Interaction devices**;

Additional Key Words and Phrases: Skin input, on-body interaction, tracking technologies

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1 INTRODUCTION

Our skin is an attractive platform for user interfaces. The skin provides a large surface for input that is always with us and that enables rich types of interaction. We can, for instance, navigate the menu of a mobile phone by sliding a finger across invisible controls on the palm [11] or control a computer by tapping shortcuts on the forearm [26]. User input can be estimated using cameras [4, 12, 42] or acoustic signals propagating on the skin [14, 26, 32].

The skin enables exciting possibilities for interaction and user interface design. First, the skin enables new input types. It can be touched, grabbed, pulled, pressed, scratched, sheared, squeezed, and twisted [53], and we easily relate meanings to these actions, such as equating a strong grab with anger. Second, skin-based interfaces free us from carrying mobile devices in our hands and extends their input areas to support off-screen input. Our skin surface is hundreds of times larger than the touchscreen of an average mobile phone [19] and can be turned into an input device using a watch or an armband worn on the body. Third, feeling input on the skin can help us achieve better user experience and effectiveness than when us ing common input devices [19].

Since the widely cited paper on skin input by Harrison et al. [14] was published in 2010, researchers have developed many novel technologies for skin-based interfaces. The pros and cons of those technologies have not been systematically compared. Moreover, we understand little about

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the benefits of skin input and how to lay out controls and give feedback on the skin. The aim of this article is to step back and synthesize what we know about human–computer interaction on the skin, and outline key challenges for research. We also aim to move beyond the oddities of individual prototypes toward some general insights on new opportunities.

1.1 Literature for the Survey

This article presents findings of a systematic literature review on skin input. We reviewed a sample of 42 papers published between 2010 and 2017 on human–computer interaction where users provide input on their bare skin. We include input types where the effector is a body part (such as the finger tip) and it is used to provide input on one's own body (such as on the forearm). Therefore, input performed with devices, such as styluses [41], input on external material on the skin [3, 52], or input on other people [33] are excluded. The interactions included are taps or gestures performed in skin contact and gestures that are not fully performed in contact but are interpreted from the contacts. An example of the latter is a double tap that is estimated from two contact on-sets that occur within a certain time interval. However, we do not include input which is performed and measured as body postures instead of skin contact, even if it would involve contact, such as pinching gestures [7, 21, 25, 29] or connecting hands [13].

We used two exact queries ("skin input" and "on-body interaction") in parallel to search literature with Google Scholar. Subsequently, we conducted a forward chaining reference search from the four earliest publications (from 2010 and 2011) in the sample [10, 12, 14, 26]. We screened through the titles and included only full papers, notes, and archived extended abstracts from posters, therefore excluding workshops, thesis works, talks, patents, and technical reports. When the title did not provide an explicit reason for exclusion, we screened the whole publication to evaluate it for inclusion. This led to a sample of 42 papers for the review.

We use the collected sample to survey what skin input is, which technologies can sense input on the skin, and how to design skin-based interfaces. In Section 2, we catalog types of skin input. The most common types are similar to the tapping and touch gestures used with touchscreens. Consequently, our understanding of user experience and performance in skin-based interaction is largely limited to these two input types. Section 3 describes technologies for sensing input on the skin and outlines their strengths and weaknesses. We find that technical performance was evaluated only in artificial conditions, such as with a single, fixed posture of the hand or with a few touch targets. In Section 4, we discuss the broader challenges of designing interfaces for the skin, for instance, how to use the shape of the body and landmarks on the skin as visual and tactile cues for input and how to design interface layouts on external displays that are easy for users to map onto the skin. On this basis, we identify and discuss the open challenges and next steps for research in human–computer interaction on the skin in Section 5.

2 INPUT ON THE SKIN

The skin is frequently touched in communication: in handshakes, patting a child's cheek, and clapping. These natural forms of interaction and the deformable, always-on, large touch-sensitive surface enable new types of input and new possibilities for expressive input. Next, we discuss how may users give input on the skin, and when are which forms of input effective.

2.1 Types of Input

The most common input type in the reviewed studies was tapping. Tapping was employed in 69% of the studies, but some of these used multiple types of input (50% of the studies used multiple input types, therefore percentages do not add up). Tapping was used in selecting *discrete touch*

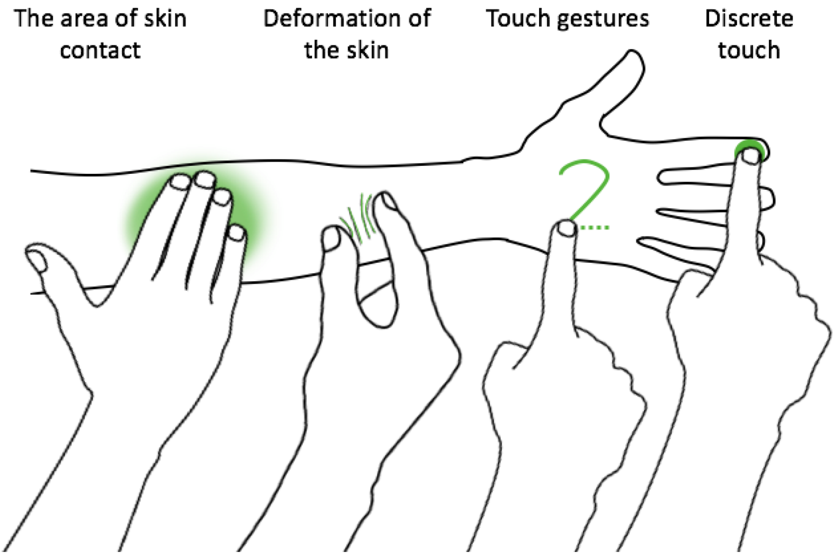

Fig. 1. The four types of skin input. *The area of skin contact* can be varied, e.g., by touching with one to multiple fingers, or by bringing some fingers or the whole palms together. *The skin can be deformed*, e.g., by pressing, pushing, or pulling the skin with one finger, or by pinching with the index finger and the thumb. *Touch gestures* include, e.g., drawing shapes, hand writing letters, or controlling a continuous slider. *Discrete touch* input can be given by tapping, or by sliding the finger on the skin and selecting a target by lifting the finger.

targets (Figure 1), similar to touching keys on a touchscreen. Another form of input for selecting discrete targets is sliding a finger across the skin and selecting the target by lifting the finger or double tapping (used in 13% of the studies). In a study by Gustafson et al. [11], participants used sliding input to find menu items of a mobile phone on their palm. When sliding across an item the participants heard the item name as audio feedback, and could select it using a double tap. Lin et al. [26] examined how many targets blindfolded participants could distinguish on their forearm. The participants were free to choose a strategy for selection. Three strategies emerged: tapping, sliding, and jumping (i.e., tapping along the forearm until the selected location is reached). Most studies (93%) used the index finger for tapping, and many (24%) also the thumb; a few studies allowed using both. Sliding input was always performed with the index finger.

Touch gestures, such as flicking, swiping, panning, zooming, and drawing shapes were used as input in 37% of the studies. These gestures are similar to those used with touchscreens. With touch gestures the users can, for instance, input letters by drawing on their palm [4, 50]. Touch gestures do not require users to input on an absolute location on the skin, but are recognized based on patterns.

Varying *the area of skin contact* by touching the skin with multiple fingers or with the whole palm was used as input in 30% of the studies. These inputs include tapping with one to four fingers [51], grasping the forearm using some of the fingers and the thumb [32], and bringing fingers or whole palms together to vary the area of skin contact between the hands [44]. The user can, for instance, select multiple targets on fewer tap locations by varying the number of tapping fingers.

In about a third (33%) of the papers, users *deformed the skin* as input. The skin can, for instance, be pressed [39], pushed [35], or pinched [34]. Deformation input can be used to select a point and a magnitude on a slider [36], for expressing emotions [53], or for controlling 3D models with just one finger [39]. Only deformation of the skin introduced new types of input compared to on-device touches.

2.2 Locations of Input

The hands and the fingers were the most common locations for input (87% of the studies), usually on the palm side of the hand. In 67% of the studies, input was given on the wrist and forearm. Other locations were also used; Mujibiya et al. [32] and Sato et al. [44] studied input on the head, Serrano et al. [45] examined input on the face for smart glasses, Lee et al. [23] used the nose for input, and Lissermann et al. [27] and Kikuchi et al. [18] studied input on the ear. The thumb was mostly used for single-handed input on the same hand's fingers, but Oh and Findlater [37] found that users also provide input with the thumb on the non-dominant hand, gripping it similarly to a mobile phone.

2.3 Evaluating Input on the Skin

The surveyed studies show that human–computer interaction on the skin is not just a concept for the future; skin input already works. The effectiveness of skin input compared to touchscreens, however, varies based on study conditions. For example, projected touch targets on the palm and forearm need to be larger for accurate tapping compared to touchscreens [12], while typing on the palm has been shown to be more accurate than on a touchscreen when the output is displayed with smart glasses and the participants' view of their hand is obstructed [49].

The user performances with input types other than tapping have rarely been studied. Therefore, the input types are hard to compare. Only Oh and Findlater [38] studied user performance with touch gestures, and no study measured user performance with gestures that vary the area of skin contact or with deformation of the skin.

The success of skin input depends on how users experience it. The studies suggested that users prefer skin input compared to input on touchscreens, especially when visual feedback is limited. For example, 9 of 12 blindfolded participants in a study by Oh and Findlater [38] preferred to tap and draw on the palm compared to a mobile phone. Serrano et al. [45] showed that participants preferred to perform gestures on their face compared to a head-worn device. Gesturing on the cheeks, for instance, was found less tiring than gesturing on the temple of smart glasses. Havlucu et al. [15] found that on-skin gestures experienced werer physically less demanding and more socially acceptable than mid-air gestures.

The studies also collected subjective measures of factors that influence the user experience, such as comfort, frustration, mental demands, preference, and sense of urgency. These were used to compare skin-based interfaces to existing interfaces [8], to compare interface layouts on the skin [49], and to evaluate input gestures [45, 48, 53]. For example, continuous tapping was found to be a preferred gesture for "force close" and "emergency call" commands, and for indicating "boredom" and "nervousness" [53]. Interestingly, participants occasionally chose uncomfortable but meaningful actions for input. For example, they preferred the input for "anger," such as twisting or squeezing the skin, to hurt a little [53].

The effects of input locations were examined both on input performance and on preference of input types. Harrison et al. [12] concluded that to achieve 95% input accuracy with their system on nine touch targets on the palm, the diameter of the targets should be 22.5 mm at minimum, and targets on the forearm that are not centered require a larger diameter of 25.7 mm. They suggested that the larger inaccuracy on the forearm was caused by the "curved" sides of the input area. Oh and Findlater [37] also found that the hand is the preferred area for input compared to the forearm, head, and face. They suggested that social acceptability of input location is more important than its ease of use and physical comfort. Weigel et al. [53] compared eight input modalities and six locations on the non-dominant hand and arm on their perceived ease and comfort. They found that the perceived ease of input modalities depends on the location. The skin on the palm, for instance, is difficult to deform (e.g., with twisting or pulling), yet it was the preferred location for touch input.

3 TECHNOLOGIES FOR SKIN INPUT

Sensing input on bare skin requires new technical solutions. Keyboards and touchscreens cover most or the whole input area with sensors, allowing robust sensing. Such direct sensing on the skin, however, requires inventive placement or implanting, and indirect sensing is less robust. Next we discuss the technical challenges in tracking input on the skin.

3.1 Types of Sensing

From the 28 papers in our sample that tracked input, three main types of sensing technologies emerged: optical sensing, sensing of mechanical or electrical changes in the skin, and touch sensors placed directly on or underneath the skin (Figure 2).

Optical sensing can be used for tracking the location of the inputting finger on the skin as a distance from the sensor (i.e., as depth). Sensing systems from this category were the most common in the studies (86%). The systems include motion capture systems, still cameras, and infrared sensors.

Motion capture systems, such as Vicon and OptiTrack, use markers attached to the skin surface (e.g., a palm) and to the part of the body that gives input. Markers can be attached, for instance, on top of the finger that is used for input to leave the fingertip uncovered [1, 11]. Those markers are tracked by multiple cameras around the user to infer their locations.

Systems using *infrared sensors and ultrasonic rangefinders* emit light or sound, which reflect from the inputting finger. The finger location is then estimated from the angle, amplitude, and other signal features of the reflection and its travel time. These sensors are small and often integrated in watches or armbands. For example, watch-based IR sensors have been pointed toward the knuckles to track taps and touch gestures on the back side of the hand [20, 24, 42, 49], and ultrasonic rangefinders pointed toward the elbow to track taps on the forearm [26]. IR sensors have also been used to measure the vertical distance from a watch to the skin of the forearm [31, 34–36]. This distance represented the deformation of the skin, and the system used it to interpret the force and direction of a finger press or pinch.

Image processing can be used for detecting the form of the skin surface. One approach is to estimate the edges of the hands and fingers by extracting the skin from the background of the images and, with these edges, classify touch locations with machine learning [46]. For example, thumb taps on the same hand's digit fingers can be estimated by classifying postures by shapes of extracted images of the skin [4] or by creating reference points on the thumb tip and on the joints of each digit, inferring the tap locations based on the closeness of those points [42]. Another approach is flood filling techniques which can be used to distinguish two surfaces or their distance from each other, and thereby estimate when touch occurs [12]. A third approach is to only process images of the skin that act as an input surface. Ono et al. [39], for instance, used optical flow vectors of a palm print and estimated the 3D force applied on the palm from the deformation that these vectors represent.

On-skin sensing was used in 46% of the studies. This is done by measuring changes in how signals propagate on and through the skin. The signals include sound and ultrasound waves, mechanical vibrations caused by taps, and impedance, indicating a change in electrical circuits involving the body and therefore a touch between two parts of the skin. Input is estimated by comparing the measured signals to signal data representing a known input. The sensors and emitters are small

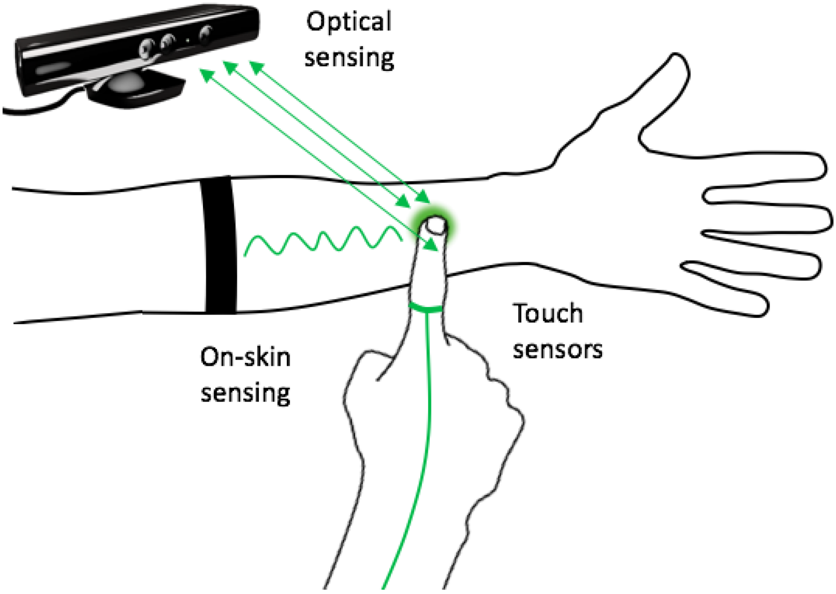

Fig. 2. The three types of sensing technologies. *Optical sensing* detects location well and can achieve large input resolution, but reliable detection of skin contact is hard. Users need to maintain certain postures so as to not obscure the line of sight to the interactive area on the skin. *On-skin sensing* is good in detecting skin contact and has been shown to achieve a resolution of 80 touch targets, but requires more processing of sensor data and is sensitive to user's movement. *Touch sensors* are excellent in detecting if skin contact occurs, and do not restrict movement, but have a binary resolution, and are hard to implement or invasive.

and can be attached on the skin outside the input area, leaving it uncovered. On-skin systems can distinguish the size of the contact area on the skin [44, 51], tap locations [14, 32], or can imply whether a tap occurred [6].

Touch sensors detect touch directly. They include capacitive touch sensors, piezo-electrical sensors, and pressure sensors. Such sensors were used in 21% of the studies. Touch sensors can be placed in three ways to enable direct sensing and touch on bare skin. First, small capacitive touch sensors can be placed on a fingertip, while still leaving most of it uncovered [8, 38, 49]. Second, the sensors can be placed behind appendages of the body, such as behind the ear lobe [27]. Third, the touch sensors can be implanted and sense touch through the skin [16]. Capacitive sensors are binary, but pressure sensors can allow detecting multiple levels of pressure through the skin [16].

3.2 Technical Performance

Recognition accuracies of the sensing systems vary between different types of sensing. Optical sensing generally performs well in detecting the location of the inputting finger on the skin but is often inaccurate in recognizing whether a touch occurred or not. The reason is that these systems cannot separate the fingertip from the skin that acts as an input surface (e.g., the palm). By using image processing for sensing, CyclopsRing achieved an 84.75% recognition rate for seven one-hand tap gestures [4], and DigiTap was able to correctly classify 91.9% of 12 thumb tap locations on the digit finger joints [42]. PalmType used IR sensors and was able to recognize an average of 74.5% of the taps on 28 keys on the palm [49].

On-skin sensing systems were used for tracking touch gestures and the area of skin contact in addition to tapping. The BodyRC system achieved 86.76% accuracy in distinguishing five locations (e.g., the nail of the middle finger) touched with one finger or the whole palm and sliding downward and upward [51]. The ultrasound sensing developed by Mujibiya et al. [32] obtained 86.24% accuracy in distinguishing grasps with one to four fingers, and 94.72% accuracy on distinguishing points on the palm and on the back of the hand.

Sensors have been combined to achieve better recognition rates of input. For example, optical systems were combined with capacitive touch sensors [8, 37, 38, 49], proximity sensors [45], accelerometers [42], and piezo-electrical sensors [20] to reliably detect touch or to trigger location sensing. Combining optical sensing and touch sensors is beneficial because the former recognizes the location of touch well, while the latter recognizes the occurrence of a touch well.

The resolution of optical sensing to track location of input is usually high. For example, the Vicon motion tracking system can track the marker position with a 1 mm accuracy [49], and the watch-based IR sensing by Lim et al. [24] was able to detect the robot finger location on the back of the hand with the x and y directional accuracies of 7.02mm and 4.32mm. In contrast, with on-skin sensing the ability to track multiple target locations depends on the signal features, and machine learning and classification capabilities of the system. The Skinput system, for instance, used on-skin sensing of acoustic signals and classified taps on 10 targets with 81.5% accuracy [14], and the SkinTrack system reached mean distance error of 8.9mm on 80 targets. With touch sensors, the number of targets depends on the number of sensors because the sensing is binary.

Only one system tracked both sides of the hand and forearm, although separately [32]. On-skin sensing was used to track input on targets placed around the forearm or the wrist, on two rows on opposite sides of the forearm, or as two single targets on both sides of the hand. Three studies tracked one side of both the hand and the forearm together with on-skin sensing [14, 51, 55]. None of the systems tracked input around the entire forearm and hand.

Movement of the user can cause noise to the signals that are tracked to recognize input, and therefore hamper the performance of tracking systems. Touch sensors suffer the least from noise, and with those, the users are free to move and change their body posture. In contrast, on-skin sensing technologies are prone to noise caused by movements of the user because the tracked signals propagate through the body, and muscle activation interferes with this.

Optical sensing places the most restrictions on the user's mobility; maintaining line of sight to the input area is necessary. Thus, most studies of optical sensing used fixed hand postures, preventing, for instance, flexion of the wrist, which could bring the input surface of the hand too close to the sensor, potentially confusing it with the finger. For example, the wrist joint was restricted to a neutral pose to track taps on the hand with cameras and IR sensors attached to a wristband [20, 24, 42], and the palm was kept flat and still by affixing it onto a table surface [49] or to a cardboard equipped with markers [8]. These approaches also help to detect when the fingertip touches the skin. Furthermore, most optical systems are sensitive to lighting conditions and need to minimize light pollution from the environment. For example, an LED flash [42] or infrared light emitters can help in highlighting the skin of the finger to distinguish it from other surfaces reflecting light further away [24, 49].

To summarize, optical sensing may achieve the highest resolution, while touch sensors may allow the most freedom to user's posture and movement. Optical and on-skin sensing show the potential for tracking many types of input, and on-skin and touch sensors can complement optical sensing for more robust touch detection.

4 DESIGNING FOR THE SKIN

As seen in previous sections, many possibilities for input on the skin exist. For other types of interfaces, we know much about how to design feedback, layout commands, and so on; how to do that for on-skin interaction is less clear. For instance, people mark their skin with make-up, tattoos, sports paints, and notes [47]; in doing so the locations and types of such marks have strong effects on how they are perceived; similarly, the location of touch on the body have personal and social significance. Next, we discuss what this means for designing user interfaces for the skin.

4.1 Mapping Input to the Features of the Skin

Layouts of input controls on the skin can be designed by simply copying the grids from keyboards and touchscreens, or by adapting the layouts to the features of the skin and to the shape of the body. Visual interfaces inevitably present some spatial layout. When the layout is presented on an external device, the users need to untangle how the displayed targets are organized on the skin (i.e., to solve the mapping). Dezfuli et al. [8] asked participants to design a mapping by placing remote control keys on their palm and fingers. The participants preferred a layout that is consistent with the keys of a conventional TV remote control. In this layout the directional keys are located at the corners of the square that the palm forms, and the selection button at the middle of the palm. Moreover, the participants preferred to hold the palm diagonally, allowing a natural alignment of the directional keys.

In addition to user preference, layout designs also influence input performance. Wang et al. [49] examined typing performance on the palm with QWERTY keys which were displayed on smart glasses. They compared a common QWERTY layout on a touchpad and on the palm, and a user-defined layout on the palm, for which the participants had designed the shapes and locations of the keys. They found that the participants typed 15% faster on a normal palm-based QWERTY layout, and 39% faster on a user-designed palm-based QWERTY layout than on a touchpad.

Common anatomical or personal features of the skin can act as **landmarks** and guide the user in input. The studies mentioned various landmarks, such as the joints of arm and fingers [11, 42], variations between concave and convex areas on the skin [8], and visual landmarks such as freckles, veins, and tattoos [9]. For example, the participants of Gannon et al. [9] used freckles and veins as guides for performing touch gestures. The participants of Dezfuli et al. [8] and Wang et al. [49] also used landmarks in placing the keys; they followed the shape of the palm.

The landmarks are suggested to help in input performance. For example, Gustafson et al. [10] used an imaginary grid layout with anchoring points on the thumb tip, the index finger tip, and the point where the thumb and index join and showed that participants tapped most accurately on those, while tapping accuracy significantly decreased the farther the target was located from these landmarks. In another paper, Gustafson et al. [11] showed that even without visual feedback, users benefited from seeing their bare hands and achieved twice as fast target acquisition speed compared to a blindfolded condition. In addition, Lin et al. [26] showed significantly higher tapping accuracies on locations at the elbow and wrist compared to the other three locations along the forearm.

4.2 Feedback for Skin Input

Skin input has been suggested to be used with desktop or remote displays (24%), smart watches (24%), smart glasses (14%), headphones (12%), projectors (5%), mobile phones (5%), and VR glasses (2%). The VR and smart glasses provided feedback elsewhere than on the skin [4, 27, 45], although they could also be used to augment the skin with visual feedback. However, none of the interfaces in our sample did so. Projectors were used for presenting feedback on the skin [12, 14], and smart watches were used for both presenting feedback on the watch face [36], and projecting targets next to the watch on the skin [22].

Users were given some sort of feedback about skin input in 24 papers in the sample; in the rest of the papers the users received no feedback, for instance when no interactive tasks were involved. Most of the interfaces provided visual feedback (83%). Out of these, 19% projected the interface and displayed feedback (e.g., indicated target selection) directly on the skin where the input was performed, allowing direct touch interaction similar to common touchscreens. Further 35% provided visual feedback on watch faces. Visual feedback was most frequently (62%) displayed outside the body surface on external devices. Audio feedback was provided in 16% of the interfaces. Surprisingly, none of the interfaces provided haptic feedback, and only one prototyped haptic output by implanting an actuator [16].

Visual feedback is important for effective input. For example, Harrison et al. [14] found that eyes-free tapping on the hand and forearm is on average 10.5% less accurate than tapping on visual targets. Lissermann et al. [27] studied tapping on the ear, where no visual guidance was available. Tapping on the ear lobe had an average accuracy of 80% on four, 64% on five, and 58% on six targets. Gustafson et al. [11] found 19% faster performance in retrieving targets on the palm by sliding input when participants were able to look at the palm compared to when they were blindfolded.

Yet, the studies suggest that skin input is possible also when a user's view of the hand is limited. For example, the average typing speed on a QWERTY keyboard on the palm was 10.5 words per minute [49], the key size needed for achieving over 90% touch accuracy on nine targets on the palm side of the hand and fingers was 28mm [8], and the average accuracy for tapping five sections on the forearm was 84% [26].

Feeling the inputting finger on the skin was suggested to help the users in finding targets without visual feedback. For example, Gustafson et al. [11] examined the importance of such passive tactile feedback using a fake palm, and therefore prevented participants from feeling their fingertip on the skin in a study condition. The results showed a 30% slower performance in finding targets on the fake palm. In addition, Lin et al. [26] found slower but more accurate target selection in using sliding input than tapping.

5 CHALLENGES FOR SKIN INPUT

The previous sections have characterized how we may give input on the skin, how that input may be sensed, and how user interfaces for the skin can be designed. Next, we discuss what we on that basis see as the main opportunities and the related research challenges for human–computer interaction using the skin. Those challenges are in part shaped by the current prototypes and studies, but are in part also about the coming years of research in on-skin input. They include how to use the skin for expressive input, how to transfer on-skin interaction from the laboratory to real use, and how to map user interfaces to the skin.

5.1 Toward Expressive Input

One expectation for on-skin input is that it can be more expressive, that is, communicate more information with better accuracy and higher resolution. Currently, however, the evidence around this expectation is limited.

One challenge is about developing adequate methods to characterize how expressive input can be, not only on the hands but across all skin areas that might be sensed. Such methods are needed to aid the development of skin input types, and to benchmark those against device-based input. For instance, the skin provides a larger touch surface than hand-held touchscreens, and can therefore accommodate more touch targets. Currently, however, we do not know how many targets users can effectively select across the entire hand and forearm (let alone other parts of the body). Using combinations of on- and off-skin input, such as with WatchSense [46], the expressiveness of commands could further be increased. This challenge also concerns how to use grabbing, pulling, scratching, and other deformations of the skin for expressive input. Whereas this forms the topic of several papers, we do not know which deformations are useful, or how many distinct commands can be communicated with deformations. Evaluating user performance with such inputs could help in characterizing the expressivity across different locations and input types on the skin.

A second challenge is to increase the tracking resolution and accuracy in detecting input; currently, we do not know how large an area and how many targets or commands can be effectively sensed. Tracking performance (e.g., the sensing accuracy across the number of targets) is one of the basic measures of any input technology, and is necessary information for choosing which technology to use for skin input. However, the studies rarely measured sensing performance separately from user performance. Following the approach of Lim et al. [24], the sensing accuracies could be measured with robots. This would help in recognizing the suitable sensors early before unnecessary work on machine learning and classification methods that are only needed for final applications to interpret real user input. Further, the resolutions and tracking accuracies of current sensing technologies could be improved by combining sensors. Optical sensing has already been successfully combined with other sensing technologies to improve recognition rates of tapping input [8, 20, 37, 38, 42, 45, 49]. Combining sensors could also allow tracking multiple input types, such as deformation in addition to tapping.

5.2 Real-Life Use of Skin-Based Interfaces

The skin is inherently a mobile and a personal interface. Using the skin poses new challenges for sensing technologies, but also new opportunities as it is an always-on surface, that is larger but leaves more physical resources free for input compared to hand-held devices. One important set of research questions concerns understanding how useful these benefits can be in real life.

First, we need to understand how accessible and effective skin input can be on the move. The studies suggest that the skin can be more accessible and usable on the move than external input surfaces because feeling touch on the skin can compensate for lack of visual feedback [8, 11, 26, 38, 49]. No study, however, has examined the effectiveness of skin input types with moving users. Evaluating physical engagement of the hands (e.g., using [40]) could reveal whether the input types that allow continuous contact and therefore more stable hands, such as deforming input, can be more accurate in mobile conditions than tapping. Microgestures, such as touch gestures on a fingertip [5], or pressing the side of the index finger with the thumb similarly to using a laptop trackpoint, could also perform well on the move while not being visible to other people. Currently it remains unclear if these benefits materialize in real-life use.

For on-skin input to be beneficial in real-life use, we need robust sensing for mobile conditions. Most of the current prototypes of skin-based touch interfaces fix the user's pose to maintain an acceptable level of tracking and projection accuracy [9, 11, 26, 32, 49]. But fixing the hand invalidates most of the reasons to use the skin instead of existing devices. Thus, evaluating the technologies with a free hand posture is necessary for finding suitable technical solutions to sense input on the skin in real application areas; that has currently not been done.

The third challenge is to ensure tolerance to other aspects of real-world use, in particular to develop sensing that works even if parts or all of the input area on the skin is covered. While we have focused on interaction on bare skin, several projects have developed electronic tattoos that cover the skin [17, 28, 54]. These tattoos reap many benefits of skin input, such as passive haptic feedback. Such sensors, as well as interactive clothing, are rather wearable than on-skin interfaces, but sensing skin input through clothing is an area worth exploring to address applicability of on-skin interfaces to different use contexts. Moreover, a gracious transition from on-skin to covered-skin interaction also seems important for real-world usage.

5.3 Designing Skin Input and Output

Input on the skin presents new opportunities because the body's shape, texture, and social role becomes a material for designing input and output, quite unlike designing for input on a touchscreen. Whereas much work has enumerated these opportunities, many research challenges remain in mapping input to the skin, and to external output.

One such challenge is to understand how location on the skin affects input and output. Projection can be used for output and for displaying the interface directly on the skin [12]. The studies show, however, that surface features and forms such as curvature and softness affect the effectiveness of input. For example, discrete touch input seems to perform worse on curved locations [14], and the possible magnitude of deformations vary across different locations on the skin [53]. Location is likely to influence the user's perception of input and output as well as their social acceptability. Currently, these remain open questions.

The second challenge for designing skin-based interfaces is to understand how to map interface elements and layouts onto the skin. The studies reviewed show findings supporting both grid layouts, similar to touchscreens, and layouts fitted to the features of the skin and the shape of the body. For example, users often prefer familiar grids [8] but perform better on layouts designed for the skin [49]. Therefore, it is important to examine how visual targets should be mapped onto the skin and how to balance between grids and body-based shapes.

Unlike direct projection [12], output displayed on an external interface poses a third challenge to mapping because that involves alignment between two surfaces: the displayed layout and the layout of input on the skin. Methods to effectively map indirect input exist and are applied, for instance, in the control-display ratios of mouse and trackpad interfaces. Such straightforward transformations, however, are not applicable to the skin because of its distinct shape and the body's varying alignment with external displays. The studies show, that in addition to locating the targets based on the features of the skin, users also align the touch surfaces to match external visual layouts [8]. Design of external output would therefore benefit from models describing the intuitive and effective mappings between skin input and external displays.

The fourth challenge for design concerns how to use haptic feedback for on-skin input. Visual and haptic cues on the skin appear to help the user in finding target locations [1, 11], but no study systematically examined the usage of haptic landmarks. The feedback perceived from touching the skin has been suggested to guide touch. Finding ways to benefit from haptic feedback is important, as well as developing new kinds of haptic feedback that users can sense on bare skin, such as those produced with Electrical Muscle Stimulation [30].

The fifth challenge for skin input is to understand what meanings touch carries to the user. Some studies have examined which input types participants preferred for given commands or emotions [38, 45, 53]. For example, Weigel et al. [53] found that continuous tapping was preferred to communicate alertness, such as forcing or emergency. No study, however, has examined what meanings skin input triggers in the user. This is important to do because understanding meanings would help in designing intuitive input and in avoiding unintentional meanings of particular touch input; for instance, to not make the user feel alert when tapping.

6 CONCLUSION

The skin is a wonderful opportunity for interaction designers and researchers. Touching the skin is a natural and important means of communication. Touch has strong effects on well-being and health, and on how people behave and feel about other people, products, and services [2, 43]. People naturally use their skin, for instance, to communicate participation to a sports team with face paint, to visualize important things with tattoos, and to remind themselves of a call by writing a phone number on the hand [47]. The skin can offer an expressive, personal, touch sensitive, always-on input surface for human–computer interaction. Leveraging skin-specific characteristics in designing user interfaces is exciting but also challenging.

The purpose of this article was to synthesize what skin input is, which technologies can sense input on the skin, and how to design interfaces for the skin. The reviewed studies show that input on the skin already works; touch was used for controlling menus, giving commands in games, drawing symbols, typing, controlling music players, and communicating emotions. The largest challenges are technical, in ensuring robust high-resolution tracking of input also in mobile real-life use. The largest opportunities are in making use of the expressive features of the skin, such as its large surface, deformation, landmarks, and new types of feedback. We hope that by addressing challenges for research in human–computer interaction on the skin, this article also helps in developing existing technologies further and in designing expressive and effective input types and interfaces for the skin.

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