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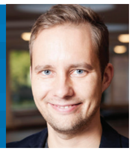

Skin—The Next User Interface

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Although there are numerous technical and ethical challenges, making sensors and output components compatible with elastic skin has the potential to offer an unprecedented level of directness and expressiveness in mobile computing.

Multitouch gestures are the main way we interact with today's mobile devices. Whether using a smartphone, tablet, or smartwatch, we control the device by touching and swiping on the touchscreen. But what's highly effective on handheld devices is a challenge on wearables. To ensure users can comfortably wear devices, the trend has been to make wearables ever smaller. As a result, their surfaces are too small for the effective and accurate gestures required to operate larger touchscreens.

Is this the end of touchscreens? Rectangular, planar, and rigid touchscreen technology certainly wasn't designed with the human body in mind. And given the problems associated with too-small touchscreens, investigating alternatives to conventional technology and miniaturizing devices to improve body compatibility makes sense. Why not use new, more body-compatible technologies to create larger, more touch-friendly devices?

It turns out that the skin itself could well be the new touch-sensitive interactive surface. Skin is an amazing organ with a number of special user-interface properties: it offers a very large surface area for input and output, and it's always with us and easy to reach, allowing direct, subtle, and discreet interactions. This is true for a variety of mobile activities, including walking, running, steering a car, or riding a bus. In both form and function, skin is ideal for human touch sensitivity, offering a soft surface that's highly sensitive and therefore capable of distinguishing between varied forms of touch.

SKIN AS AN INTERACTIVE SURFACE

Whether you're in a foreign city or on a hiking trip, interactive skin might allow you to quickly access directions. Either side of your hand could display a map with directions on demand.[1,2] No need to pull a device out of your pocket or use the tiny display on a smartwatch. You might also be able to use your skin to control your smartphone's functionality. For instance, while running, you could accept calls or control the music player with subtle gestures, such as by touching your thumb to an adjacent index finger.[3]

The dexterity of touch combined with skin-based tactile feedback allows for accurate interactions while on the go that require only one hand and no visual reference point. In addition, interactive skin might draw upon the high expressivity of human touch to extend remote communication beyond the audiovisual channel. For instance, you could send a tactile emotional message to a loved one from a distance, such as with a reassuring squeeze of the hand or a tender caress.

For this vision to become a reality, we need to solve three main problems.

First, how can skin-based interactions be usable, useful, and socially acceptable? Clearly, skin differs significantly from a touchscreen, not only in terms of its geometry but also in its primary function and possible interaction modalities. We must also consider the social implications of touch. Existing principles for touchscreen user interfaces can't simply be transferred to skin, as this doesn't account for its unique characteristics.

Second, what's the best way to sense input and provide output through the skin? Those properties that make skin an amazing organ also make it a tremendous challenge for engineering user interfaces. Unlike touchscreens, skin is curved, even stretchable, and thin. These properties require different technical solutions for capturing user input and for providing visual or tactile output.

Third, a set of important questions extend beyond the core of computing: How can we integrate computing on the human body in a way that is safe and doesn't compromise health? How can we ensure it is acceptable from an ethical perspective, and how far should we go in blending humans and computers? How can we prevent the misuse of highly personal body data, including data from biosensors? These questions require an intense cross-disciplinary discourse as well as a new set of methods and standards for the engineering of body computers.

A new research stream in human–computer interaction—at the intersection of interaction design, electrical engineering, and new materials—is providing some preliminary answers to these questions.

USING SKIN TO INTERACT WITH COMPUTERS

Pioneering work has proposed the placement of on-skin user interfaces on the user's hands, fingers, wrist, or forearm. These are suitable locations mainly because they're are easy to reach and socially acceptable to touch. More unconventional locations also have been proposed, such as the face, belly, and back of the ear (for example, to control a headset). Most work has investigated rather simple forms of input that are mainly inspired by touch gestures on conventional touchscreens. For instance, users can enter a symbol or a character on the skin[4] or select an option by tapping on a button or a menu option that is projected onto skin.[2]

It's unclear, however, how best to design new forms of input that take into account skin's unique properties. Which gestures complement the curved geometry of body locations? How can we cope with the fact that the surface isn't rigid, but soft and stretchable? And how can we make use of tactile body landmarks to guide eyes-free interaction?

To provide initial answers to these questions, my research group conducted an empirical user study.[5] Our goal was to determine user preferences for on-skin control of mobile devices. In particular, what kinds of gestures can users perform on skin, and what are the characteristics of skin-specific input modalities? Rather than providing the participants with any existing technology that might bias and restrict their thinking, we asked them to interact on their own skin without any technical augmentation and imagine that their skin would sense their input by some yet-to-be-invented means. We gave each participant a set of commands related to typical smartphone tasks and remote communication (such as copy, undo, delete, accept call, confirm, and express sympathy). The task was to devise and demonstrate at least one gesture for each command and do so quickly and intuitively. This empirical approach, called an elicitation study, is an established approach for understanding user preferences and for compiling design recommendations.

The study revealed that skin input has dual characteristics. First, it's compatible with many existing smartphone gestures. Participants successfully transferred common multitouch gestures from touchscreens to skin input. This held true for typical well-established commands common on smartphones, such as zooming in and out, swiping left or right, and moving an item.

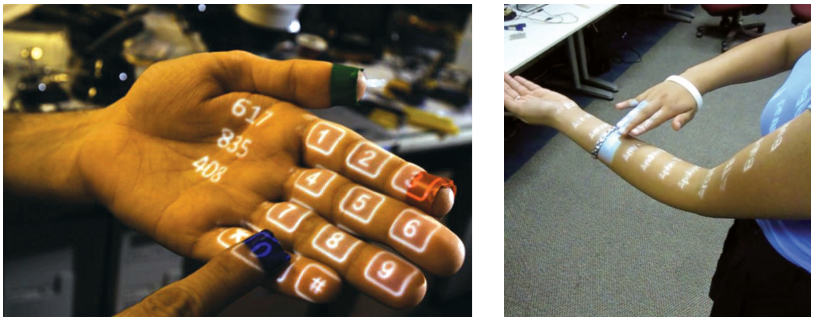
Second, our study showed that the unique properties of skin also allow for new gestures that are far richer and more expressive than conventional multitouch gestures. The study participants performed them frequently for commands related to expressing an emotion and for those that were important or irreversible. Such varied interactions included grabbing, pressing into skin, pulling skin up, twisting, or shearing (see Figure 1). For example, many participants expressed sympathy by gently stroking their forearm, taking inspiration from interpersonal touch, and they expressed anger by punching the palm with force. To avoid accidental activation, users deleted items by pressing forcefully or scratching with all fingers. Users indicated they even explicitly desired a degree of slight physical discomfort for some types of commands to ensure they were aware of performing them.

Tactile landmarks on the body such as bones, wrinkles, and knuckles can be of great help too. These areas can guide users to the correct location without requiring them to look at their hands. This results in skin user interfaces that are easier and faster to interact with, particularly for activities performed on the go and requiring the user's vision—such as steering a car. Pioneering work has demonstrated the benefit of tactile landmarks for interaction on the palm and the underside of the fingers.[6] Other body locations have yet to be investigated.

Skin offers even more degrees of freedom for input. For instance, touch input on skin may be combined with hand and arm gestures,[1] and we could use clothing as an additional control.[7]

Certainly, research in this area is still in an early stage. Existing work consists of point probes for one or a few specific body locations and exemplary types of interaction. The larger picture has yet to be developed. A broader and more coherent understanding of the interaction space will allow us to integrate interactions and deploy them in real-world applications. The practical success of skin interaction will also depend on solving a crucial challenge: How can we reliably distinguish between gestures that the user purposefully makes to communicate with a computer device and the touch events that stem from common activities, such as touching or grabbing a real-world object?

Figure 1. Skin-based interaction. Skin enables versatile and highly expressive forms of input that go far beyond the capabilities of conventional touchscreens.



(a) (b)

Figure 2. On-skin input and output technologies. (a) Armura and (b) Sixth Sense use a camera and a projector to make skin interactive. (Source: Pattie Maes and Chris Harrison; used with permission)

TECHNOLOGIES FOR ON-SKIN INPUT AND OUTPUT

How can we make skin interactive? Most prior work has addressed this challenge by using off-the-shelf depth or RGB cameras, mounted on the chest, shoulder, or wrist to capture touch input. High-resolution visual output can be projected onto skin using a body-mounted projector (see Figure 2).[1,2,8] The benefit of this approach is that skin itself remains unaugmented, resulting in a fully natural skin-touching sensation. Moreover, it lets us use off-the-shelf hardware. However, the inherent limitations of camera-based systems include inaccurate touch-contact detection, making precise gesturing difficult; line-of-sight requirements restricting the supported set of body locations; and lighting issues that restrict outdoor use.

Other frequently studied sensing techniques for touch input on human skin involve acoustic, magnetic, infrared, and capacitive sensors. Magnetic sensing, using a grid of Hall-effect sensors and a magnet, has demonstrated the highest spatial resolution thus far.[4] However, these existing approaches still can't accurately detect touch contact, which is a prerequisite for common touch gestures. Very few research endeavors have looked beyond touch into other more skin-specific modalities. A notable exception is a proposed custom infrared-based sensing technique to capture a lateral stretch of the skin that results from shear input on the forearm.[9]

Stretchable and epidermal electronics take a different approach, and they make it possible to create stretchable and thin (less than 0.1 mm) sensor surfaces that are more like skin. Worn as an adhesive patch or tattoo, these technologies closely conform to human skin and allow for natural body movement.[10] As active electronic components are embedded, this approach could offer more accurate sensing, including a high spatial density and precise detection of touch contact. Additional input and output modalities can be included, such as pressure sensing, sensing of biosignals, active visual output, or haptic output. This makes it a compelling new technology

Figure 3. Aesthetic on-skin devices. The iSkin touch sensor is thin and stretchable. Using digital fabrication, it can be customized to fit the user's aesthetic preferences and individual proportions so it can be worn at various locations on the body.

for interactive skin user interfaces,[3] although challenges remain, such as how to make the electronic overlay fully compatible with the natural physiological functions of skin, including thermal regulation, sweating, and undiminished tactile sensitivity.

Thus, it's already possible to sense touch input and provide visual output on various body locations, but current approaches offer rather low spatial resolution and limited accuracy. Input beyond touch contact is still uncharted territory. Rapid progress in this area promises to improve capabilities and alleviate or overcome many of these restrictions. New approaches based on epidermal electronics, radar, or electromyography (EMG) are also on the horizon.

PERSONALIZED AND AESTHETIC ON-SKIN DEVICES

Compared with established off-body computers, on-skin computing devices must deal with several important new variables. First, the physical context is highly varied. Geometries vary across body locations and will differ for each user. Second, on-skin devices share similarities with fashion accessories. Hence, aesthetics will become a prime requirement. Together, these points imply that both the shape and appearance of on-skin devices will be much more varied and personalized than those of the computing devices we're using today.

To enable personalized on-skin devices, we have developed iSkin, a stretchable sensor surface for touch input on human skin (see Figure 3).[3] The sensor, made of skin-compatible silicone, supports multiple sensitive areas and captures two levels of normal force.

To make it easy to personalize both the shape and visual appearance of the iSkin sensor, we developed a digital fabrication approach. That is, in a vector graphics application, an existing graphic, such as tattoo art, can be transferred into a functional sensor tattoo. The thin and stretchable sensor enables several new types of wearable devices. For instance, iSkin can produce an interactive finger tattoo that wraps around a finger for one-handed input. Attached to a conventional wearable device, it can feature an on-demand extension. For instance, we have realized a full-featured keyboard that can be rolled out of a smartwatch. Lastly, iSkin can be used to create touch-sensitive skin stickers, a sort of interactive tattoo that can be applied on various skin locations to capture touch input.

Interactive skin raises a set of challenges that are fundamentally new as computers evolve from self-contained devices, to merge with the human body, the computing community and consumer electronics industry must establish a set of methods, procedures, and best practices, similar to the medical technology field, for human-based research and product development.

Novel sensing and output technologies and skin devices must be proved safe from a health and medical point of view. Ensuring user privacy is also essential—although it will be especially challenging given the fact that skin-based computers will likely have access to far more sensitive personal data than any computing device before. Lastly, fundamental ethical questions exist in terms of how far to move forward with integrating humans and computers and for which applications. It's important that consensus on these issues be reached through cross-disciplinary collaboration among experts beyond just engineering.

Efforts to address these vulnerabilities and ensure safety are essential because skin, with its unparalleled sensitivity, has astonishing interactional capabilities that should be leveraged for computing. If done right, interactive skin-based computing has the potential to become the next user interface for mobile computing with an unprecedented level of directness and expressiveness.

REFERENCES

1. C. Harrison, S. Ramamurthy, and S.E. Hudson, "On-Body Interaction: Armed and Dangerous," *Proc. 6th Int'l Conf. Tangible, Embedded and Embodied Interaction* (TEI 12), 2012, pp. 69–76.

2. P. Mistry, P. Maes, and L. Chang, "WUW - Wear Ur World: A Wearable Gestural Interface," *CHI 2009 Extended Abstracts on Human Factors in Computing Systems*, 2009, pp. 4111–4116.
3. M. Weigel et al., "iSkin: Flexible, Stretchable and Visually Customizable On-Body Touch Sensors for Mobile Computing," *Proc. 33rd Ann. ACM Conf. Human Factors in Computing Systems* (CHI 15), 2015, pp. 2991–3000.
4. L. Chan et al., "Fingerpad: Private and Subtle Interaction Using Fingertips," *Proc. 26th Ann. ACM Symp. User Interface Software and Technology* (UIST 13), 2013, pp. 255–260.
5. M. Weigel, V. Mehta, and J. Steimle, "More Than Touch: Understanding How People Use Skin as an Input Surface for Mobile Computing," *Proc. SIGCHI Conf. Human Factors in Computing Systems* (CHI 14), 2014, pp. 179–188.
6. S. Gustafson, C. Holz, and P. Baudisch, "Imaginary Phone: Learning Imaginary Interfaces by Transferring Spatial Memory from a Familiar Device," *Proc. 24th Ann. ACM Symp. User Interface Software and Technology* (UIST 11), 2011, pp. 283–292.
7. S. Olberding et al., "AugmentedForearm: Exploring the Design Space of a Display-Enhanced Forearm," *Proc. 4th Int'l Conf. Augmented Human* (AH 13), 2013, pp. 9–12.
8. C. Harrison, H. Benko, and A.D. Wilson, "Omnitouch: Wearable Multitouch Interaction Everywhere," *Proc. 24th Ann. ACM Symp. User Interface Software and Technology* (UIST 11), 2011, pp. 441–450.
9. M. Ogata et al., "Senskin: Adapting Skin as a Soft Interface," *Proc. 26th Ann. ACM Symp. User Interface Software and Technology* (UIST 13), 2013, pp. 539–544.
10. D.-H. Kim et al., "Epidermal Electronics," *Science*, vol. 333, no. 6044, 2011, pp. 838–843.

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