On-Skin Interaction Using Body Landmarks

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The human skin is a promising surface for input to computing devices but differs fundamentally from existing touch-sensitive devices. The authors propose the use of skin landmarks, which offer unique tactile and visual cues, to enhance body-based user interfaces.

Recent research in human–computer interaction (HCI) has recognized the human skin as a promising surface for interacting with computing devices. The human skin is large, always available, and sensitive to touch. Leveraging it as an interface helps overcome the limited surface real estate of today's wearable devices and allows for input to smart watches, smart glasses, mobile phones, and remote displays.

Various technologies have been presented that transform the human skin into an interactive surface.[1] For instance, touch input has been captured using cameras,[2] body-worn sensors,[3,4] and slim skin-worn electronics.[5–7] Output has been provided using projectors, thin displays,[7] and computer-induced muscle movement.[8] Researchers have also developed experimental interaction techniques for the human skin; for instance, allowing a user to activate an interface element by tapping on a specific finger location[9] or by grabbing or squeezing the skin.[10]

To keep the design and engineering tractable, most existing work has approached the skin as a more or less planar surface. In that way, principles and models for designing interaction could be transferred from existing touch-based devices to the skin. However, this assumes that the resolution of sensing or visual output on the skin is as uniform and dense as on current touch devices. It is not; current on-skin interaction typically allows only touch gestures or tapping on a few distinct locations with varying performance and, therefore, greatly limits possible interaction styles. It might be acceptable for answering or rejecting a phone call, but it is not powerful enough to allow expressive interaction with a wide range of user interfaces and applications.

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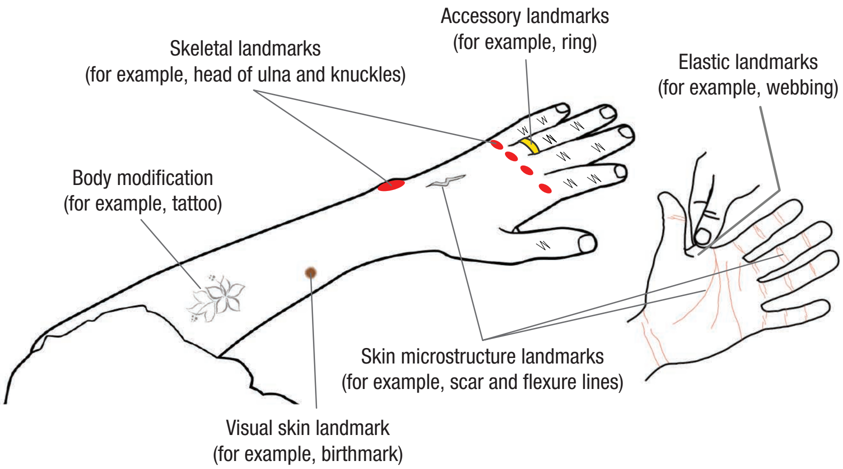


FIGURE 1. Examples of body landmarks.

More importantly, this line of thinking does not consider the fact that the human skin has unique properties that vary across body locations, making it fundamentally different from planar touch surfaces. For instance, the skin contains many distinct geometries that users can feel and see during interactions, such as the curvature of a finger or a protruding knuckle. Skin is also stretchable, which allows novel interactions based on stretching and deforming. Additionally, skin provides a multitude of sensory cells for direct tactile feedback, and proprioception guides the user during interaction on the body.

BODY LANDMARKS FOR INTERACTION

We propose using landmarks on the human skin to enhance body-based interaction (see Figure 1). Adapting definitions from anatomy, geography, and the arts, we define landmarks as unique and unambiguous locations on the human skin that can act as references for users to locate and identify points of interest and interaction. For example, the distinct visual or tactile properties can allow users to easily and quickly locate the landmark, either by looking at the skin or by simply feeling it during eyes-free interaction.

This article addresses three main challenges that must be solved to enable interaction on body landmarks:

- identifying the types of landmarks that are beneficial for HCI;
- developing technological solutions to enable interactions on those landmarks, which are characterized by challenging curvature, stretch, and mechanical strain; and
- empirically assessing the benefits of landmarks for interaction.

We present work conducted in our Saarland University[7] and University of Copenhagen[11] labs, and contribute a synthesis of landmark types and characteristics that are important for the development of technologies and user interfaces.

BENEFITS OF BODY LANDMARKS FOR INTERACTION

Body landmarks have long been used in various disciplines, including the medical sciences, anthropology, and the fine arts. In these contexts, landmarks mainly act as unique and unambiguous references on or inside the body, for example, to locate points and areas of interest, to compare biological shapes, or to measure anatomy. In the visual arts, for example, body landmarks help artists find forms and assess body proportions. In contrast, in the anatomical sciences, landmarks are defined as "structurally consistent loci which can have evolutionary, ontogenic, and/or functional significance."[12]

In HCI, body landmarks enhance user interaction. We define such landmarks as locations on the body that are tactually or visually distinct from the surroundings. They offer three main benefits for on-body interaction:

- *Localization of interactive elements*. Landmarks help users localize interactive elements on the body by leveraging human sensory and motor capabilities. For instance, the tactile features and natural divisions of finger segments allow for localizing user interface elements when operated eyes-free, that is, without looking at the interface or input device.[9]
- *Guidance through affordances and constraints*. Landmarks provide affordances that inform how to interact on a specific user-interface element and that guide input on the element. For instance, the wrinkle between two segments of a finger affords sliding along it, whereas the soft webbing between two fingers affords pressing or stretching.
- *Mapping of functionality*. Landmarks can help users memorize mappings between body locations and interactive functionality. A landmark can act as a simple visual or haptic cue that reminds users about the presence of an input widget on their body. Landmarks can also draw on semantic associations with specific loci on the body.

BODY LANDMARKS

Human body landmarks are visually or tactually distinct from their surroundings, and can be used to inform the development of technologies and interaction techniques.

TYPES

The six main types point to specific anatomical characteristics or features created by body adornments or accessories.

ANATOMICAL CHARACTERISTICS

Skeletal landmarks are characterized by their curved geometry, created by underlying bones and joints. The protruding geometries can be felt and guide or constrain on-body touch input. Examples include finger segments, knuckles, and elbow joints.

Skin microstructure landmarks are fine textures on the skin. They vary from their surroundings in their tactile perception and visual appearance, and can be used for guidance during highly localized on-skin interactions. Examples are wrinkles, flexure lines, nails, scars, and eyebrows.

Elastic landmarks have a different elasticity than their surroundings. This enables unique skin-specific interactions, such as shearing, stretching, and squeezing, for continuous and expressive on-body input. Examples include webbing, earlobes, tendons, ligaments, and muscles.

Visual skin landmarks stand out because of their visual properties. Their visual cues support spatial mappings and provide cues for localization, and their shapes afford different touch interactions. Examples are birthmarks, moles, and veins.

BODY ADORNMENTS AND MODIFICATIONS

Body modification landmarks alter the body's visual appearance or tactile perception. This allows for additional and user-defined landmarks. Examples include tattoos, makeup, nail art, henna, tan lines, piercings, tunnels, and subdermal implants.

Accessory landmarks can be easily added to the body by attaching external objects, which create visually or tactually distinct areas on the body. Examples are rings, necklaces, and wristbands.

CHARACTERISTICS

Landmark properties set requirements for technology and provide possibilities for interface design.

TYPES OF LANDMARKS

To inform the development of technologies and interaction techniques, we identified six main landmark types on the human body that are visually or tactually distinct from their surroundings: skeletal, microstructure, elastic, visual, body modifications, and accessory. Each type points to a specific anatomical characteristic or a feature created by a body adornment or accessory. One body location, for instance, the finger, can host many types of landmarks. In addition to the landmark types, we identified four important landmark properties: their commonness, their permanence, user control, and feedback. These landmark types and properties are summarized in the "Body Landmarks" sidebar.

ENABLING INTERACTION ON LANDMARKS

Body landmarks' tactile and visual properties offer desirable benefits for on-skin interactions. But how do we technically enable user input and system output on such landmarks, which can be highly curved, elastic, or small?

We recently proposed using very thin and conformal skin electronics for doing so.[7] Our sensors and displays, called SkinMarks, are based on temporary rub-on tattoos that closely conform to the skin and its landmark geometries (see Figure 2). SkinMarks can transform the user's skin into an interactive surface. For instance, a tattoo can contain multiple buttons and sliders. It can also provide visual output on the user's body, for example, by notifying the user about an upcoming event by lighting up specific tattoo segments.

FABRICATION OF CONFORMAL SKIN ELECTRONICS

Skin-worn electronics should not only be slim and deformable but also easy to personalize to fit a given user's body proportions or personal landmarks. We therefore opted for a printed electronics approach that consists of creating a digital design in a vector graphics application, which is then printed on commercially available temporary tattoo paper. We chose screen printing for our fabrication process because it supports various functional inks and allows custom-shaped, high-resolution, and personalized sensors.[13] We print one or

Therefore, it is important to know how common the landmarks are across users, when the landmarks exist, whether their presence can be controlled, and how users can perceive and use them.

COMMONNESS (GENERIC TO PERSONAL)

A landmark can be present on all humans or unique for an individual. For example, the presence and location of birthmarks and scars vary from person to person. Landmarks that are generic across people, such as bones, joints, and fingertips, can be used consistently by most users.

TEMPORALITY (PERMANENT TO TEMPORARY)

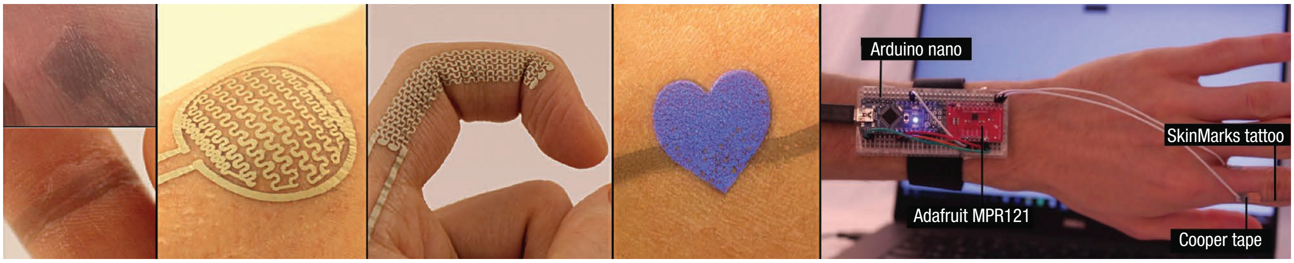
Landmarks vary in their permanence. Some landmarks, such as skeletal landmarks and permanent tattoos are permanent because they cannot be easily removed or altered. In contrast, temporary landmarks can be easily created, altered, and removed, such as accessories and makeup. Temporary landmarks can also be characterized by their frequency and duration. For example, makeup is often worn during the day and washed off at night.

CONTROL (INVOLUNTARY TO USER-CONTROLLED)

Landmarks offer users different levels of control. Some landmarks appear spontaneously or involuntarily, while others are controlled by the user. For example, skin reactions can create landmarks such as goosebumps, tan lines, or skin irritations. Users can actively add and adapt other landmarks. For example, flexing the hand into a fist exposes the protruding knuckles, whereas extending the fingers retracts the knuckles. Also, the elasticity of the webbing can be dynamically modified by spreading the adjacent fingers, and the geometry of the knuckles at the base of the fingers change depending on the fingers' flexion.

FEEDBACK (VISUAL AND TACTILE FEATURES)

A landmark can provide visual cues, tactile cues, or both. Tattoos, for instance, have not only a strong visual component but also a fine haptic texture. A protruding knuckle offers more distinct tactile feedback, easing eyes-free input, but can also be easily seen. In contrast, the variation between harder and softer skin might not be as visually distinguishable.

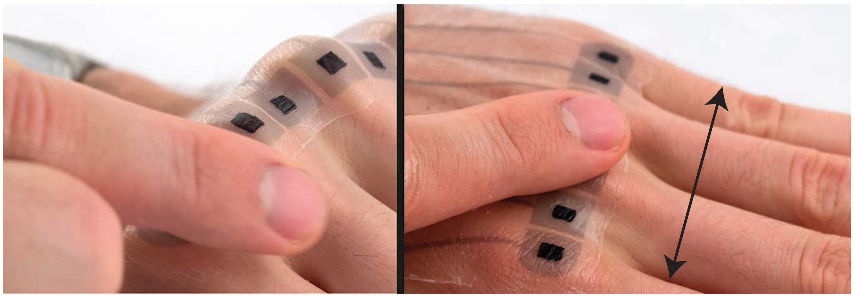


(a) (b) (c) (d) (e)

FIGURE 2. SkinMarks sensor and display types: (a) capacitive touch buttons and sliders, (b) squeeze sensors, (c) bend sensors, and (d) electroluminescent displays. (e) In our prototypes, the interactive tattoo is wired to a body-worn microcontroller.

multiple layers of functional inks. These inks add interactive functionalities, such as buttons, sliders, and displays, to the tattoo. Although the fabrication is inexpensive, printing currently requires manual steps. We envision automating these steps in the future to allow for fully automated, on-demand SkinMarks prints.

After printing and heat curing (which is required to activate the functional properties of the inks), the temporary tattoo is ready for application on the user's skin. The tattoo is wired to a body-worn microcontroller, which is currently external to the tattoo. In the future, SkinMarks could use coin-sized microcontrollers that reside on the tattoo and communicate with other mobile devices over wireless protocols, such as Bluetooth Low Energy.



(a) (b)

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

SkinMarks support four interaction modes on the body landmarks (see Figure 2):

- *Touch*. The touch sensors are based on capacitive sensing and require only one ink layer. They support touch input on very small and narrow landmarks, as well as highly curved ones.
- *Bend*. Bend sensors detect moving body parts, such as finger movement. These can allow for interface elements that react to dynamic pose changes.
- *Squeeze*. Skin allows for more input modalities than classical touch contact alone. We demonstrate that SkinMarks can sense squeeze deformations as an additional input. The squeeze input deforms the skin and results in compressive strain on a printed strain gauge.
- *Display*. SkinMarks support visual output on the skin. The tattoos can contain one or multiple interactive segments that light up. The color of the electroluminescent ink used determines the display's color.

We assessed SkinMarks' technical characteristics in a series of experiments. Scanning electron microscopy revealed that tattoos containing touch sensors are 4 μm thick, with the electrodes being only 1 μm. Tattoos containing displays are approximately 30–45 μm thick. This is considerably slimmer than the human skin itself, and even smaller than the diameter of typical human hair. This yields a highly conformal fit on the skin, even to wrinkles, which is an essential property to ensure that SkinMarks function on complex body geometries and fine skin microstructures. Our results further show that human users can apply a tattoo with submillimeter accuracy on a body landmark, and that very small touch sensors (0.25 mm wide) allow for robust touch sensing.[7] These findings demonstrate that SkinMarks interactive tattoos are compatible with small, fine body landmarks.

INTERACTION ON LANDMARKS

Based on the landmark classes and the supported interactive elements, we identified six novel interaction techniques to improve mobile computing, described here.

Tactile Cues on Skeletal Landmarks for Eyes-Free Input

The prominent geometric features of skeletal landmarks can provide beneficial cues for on-skin input (see Figure 3). We demonstrate this principle on the highly curved knuckles, which provide four distinct peaks and three valleys. Each peak and valley can act as a touch button that is associated with a different function. The distinct elements can be localized without visual attention.

Dynamic Interface Elements Using Pose-Based Input

Body movement allows for dynamic interface elements using pose-based input. SkinMarks can capture these body poses and dynamically adapt the interface. For instance, when the user is making a fist, the knuckles have a high curvature, clearly exposing the knuckle peaks. This allows for locating discrete touch buttons. In contrast, while making a flat hand, the knuckles form a relatively flat surface, which allows for continuous sliding (see Figure 3b)

Precise Touch Input on Skin Microstructure Landmarks

SkinMarks support small and narrow landmarks, with preserved tactile properties. We demonstrate this with a new interaction technique that makes use of tactile skin surface structure (see Figure 4). In one example, the user slides over the wrinkle on a finger to set a value (Figure 4a). The wrinkle guides the user's input with passive tactile feedback to improve eyes-free interactions. In another example, the user activates a toggle by moving over the wrinkle and back (Figure 4b). The wrinkle's tactile feedback helps the user localizing the toggle. Both techniques allow for one-handed input.

Expressive Deformation Input on Elastic Landmarks

Localized deformation input enriches the input vocabulary of landmarks. We demonstrate deformation input on the circular protrusion near the wrist, which gives visual and tactile cues. In our example, squeezing the tattoo can be used to capture virtual objects, such as treasures or Pokémon, in augmented reality games.

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, we implemented a touch-sensitive heart-shaped display to augment a birthmark. The tattoo notifies the user about the mood and availability of a loved one. Touching it could send the heartbeat to this person (for instance, if the loved one sends a message, the display could flash like a heartbeat) or start a call.

Interaction on Passive Accessories

To demonstrate the feasibility of accessory landmarks, we designed a SkinMarks tattoo that can be worn underneath a wedding ring. It enables subtle communication between two partners. A partner's ring gets illuminated when the other's ring is touched. The tattoo features a display that extends slightly beyond the ring; furthermore, it can capture touch input on the ring, which is capacitively coupled to the sensor in the tattoo.

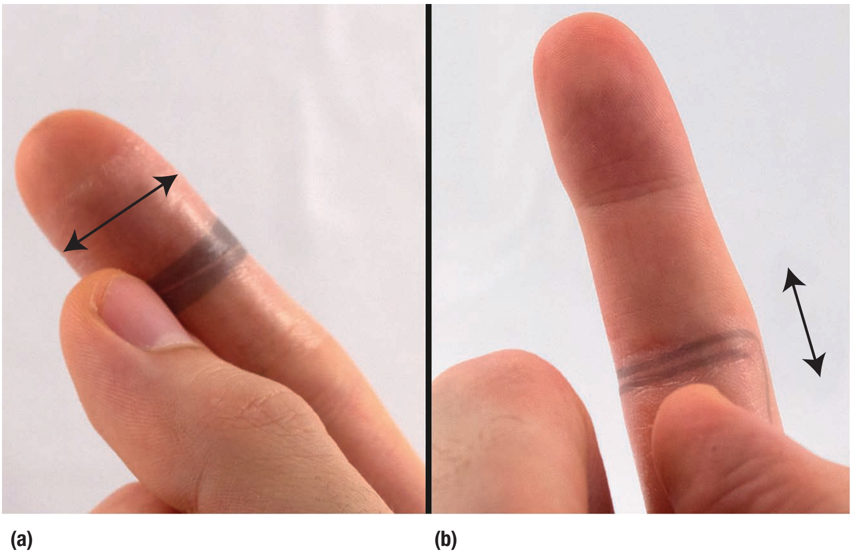


FIGURE 4. SkinMarks allow for precise touch input on skin microstructures: (a) sliding along a wrinkle for continuous feedback, and (b) crossing a wrinkle for discrete toggle input.

HOW WELL DO LANDMARKS SUPPORT INTERACTION ON THE BODY?

Having discussed how interaction on landmarks can be realized from a technical perspective, we next discuss how landmarks are used for interaction. Landmarks can help in localizing touch targets, especially when users receive no direct visual indication of the location of interactive elements on the skin.

We investigated the use of landmarks in a study in which participants first mapped such virtual elements on their hand and forearm and then attempted to recall the locations. We aimed to identify whether people make use of landmarks when mapping items on the skin, and when they do, what types of landmarks they use, how they decide which to use, and what are the benefits of landmarks for localizing virtual items.

We asked 16 participants to map 30 items to the skin by touching the locations they found suitable for each, spanning emotions, places, occupations, and family members. Participants were free to imagine associations of these items to functionalities; for instance, family members and occupations, such as dentist or lawyer, could serve as contact shortcuts for calling or texting; emotions as emojis; and places as application widgets or commands, such as for an online supermarket or a mobile bank. In addition to studying how the participants mapped and located these items on the skin, we investigated the strategies they used for associating the items with landmarks on their skin.

For analysis, we captured touch locations on the skin using a high-precision motion capture system (OptiTrack with eight Flex13 cameras and 120-Hz sampling rate). An additional high-resolution DSLR (digital single-lens reflex) camera captured images of the forearm and its skin features. Figure 5 shows the study's overall setup; more details can be found in

FIGURE 5. Study setup for tracking touch locations on bare skin and capturing images of landmarks on the hand and forearm.

Joanna Bergstrom-Lehtovirta and her colleagues' conference paper.[11]

Linking items to landmarks

To examine what kinds of landmarks were used and how often, we coded the locations of items based on touch coordinates and captured images; new landmark types were created during that process as they emerged. Overall, 52 percent of items were placed on identified body landmarks. Initially, we divided the skin into five areas: fingers (39 percent of all items), hand (17 percent), wrist (6 percent), arm (35 percent), and elbow (3 percent). For fingers, we found that participants used nails and knuckles the most, but locations such as joints and phalanges to a considerably lesser extent. The items most commonly placed on finger landmarks were assigned to family members.

We also found that participants used distinct landmarks beyond their fingers. These included the bones on the back of the hand and the wrinkle close to the elbow when the arm is flexed. Additionally, birthmarks, moles, and freckles were used for 7 percent of all items. Personal landmarks, such as tattoos, were used for 2 percent of all items. Scars, on the other hand, only accounted for 0.2 percent of items, but there were fewer scars that could be identified as landmarks in the first place. Contrary to fingers, items placed on the arm were usually emotions and places. It's noteworthy that 89 percent of items placed on tattoos were emotions.

Placing virtual items on landmarks was particularly important for their localization: landmarks serve as anchors, and without them, the item's exact locations were hard to recall. In two recall phases (after placement), participants were able to retrieve 19.8 and 21.2 item locations out of 30, respectively. Whereas fingernails resulted in a 78 percent recall rate, personal landmarks improved recall even more: tattoos had a recall rate of 82 percent, and scars 100 percent.

Placement strategies around landmarks

We interviewed participants after the study to better understand the mental strategies they used when placing items. One important outcome was that all participants employed an anchor and association mapping in at least one instance. That is, they first placed an item as anchor on a landmark (for example, a museum on a birthmark), and subsequently placed items related to the anchor closely around it (for example, supermarket, park, and library) to create a semantic cluster, similar to how smartphone users might cluster their applications menu. Using anchor items as starting points for localization also later helped the participants retrieve the locations of other items in the cluster.

Even for the abovementioned strategy, a key tactic was to associate an item with a landmark. Similar to how landmarks might be personal or generic, items are based on either personal experiences or shared experiences (that is, common among people). Personal experiences were most often linked to generic landmarks. For example, placing "mother" on the index finger came from one participant's association of a mother giving directions. Often, personal experiences were linked to personal landmarks, for instance, placing a negative emotion on a specific tattoo. Common experiences were linked to both personal and generic landmarks. For example, linking a negative experience to the middle finger (generic landmark) stems from a shared cultural background. Likewise, placing "hospital" on a scar (personal landmark) is a shared association.

Our results showed that participants used both generic and personal landmarks, and both were further linked with both shared and personal experiences. Interface designers, however, should be careful when using personal landmarks. Because not all users might have them (for instance, tattoos are not always present), and because they might not be in the same place even when present (for example, visible veins). Thus, allowing for flexible locations for such landmarks is important.

Our recent work demonstrates that interactions on various types of body landmarks can be technically enabled using skin electronics, and that landmarks offer important interactional benefits for on-body interaction. Yet, our prototypes and studies have limitations, and many important questions remain to be investigated: How to increase the resolution of input and output, to become more similar to the quality of a conventional touchscreen? How to include a wider range of modalities inside interactive tattoos, including physiological sensing or haptic output? And how to prevent everyday body movements from triggering false activations?

A major challenge for flexible sensors and displays is the integration of rigid components, such as controlling units and energy supply. We tethered our tattoos to a conventional microcontroller and battery, placed near a tattoo, for instance, at the user's wrist. Although this is a viable approach for interactive prototypes, it does not generalize to commercially deployed solutions because the fragile connections limit the tattoo's durability. In the future, SkinMarks could use flexible batteries or harvest energy from the environment, and integrate pinhead-sized microcontrollers right on the tattoo that communicate with other mobile devices over wireless protocols. Future work should also investigate pathways toward reusable devices. The key will be to identify combinations of substrate materials and skin adhesives that are robust to wear and tear and offer strong adhesion while being conformal to the skin and easy to remove and reapply.

Moreover, our findings suggest that landmarks can be user specific. Hence, how can users be best supported to realize personalized designs that are tailored to their capabilities, preferences, and personalized landmark mappings? Doing so might involve software that automatically generates an optimized electronic design and tools that allow one-step printing.

But skin interaction research faces many more challenges. In particular, we need to understand more fully what makes the body special as an interaction surface. This will allow us to more effectively drive technology design and avoid unsatisfactory interaction forms. We must also understand the social implications of touching and pinching your body as input, as well as the aesthetic benefits of and individual reservations about skin electronics. These factors are likely crucial to uptake but are not well understood. Finally, the link between our bodies and how we feel and think differs dramatically different from that between devices and how we feel and think. Research is just beginning to use those links in technology design and exploit the body's special relation to the sense of agency, intimacy, and proprioceptive feedback. C

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