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

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ABSTRACT
This paper contributes results from an empirical study of on-skin input, an emerging technique for controlling mobile devices. Skin is fundamentally different from off-body touch surfaces, opening up a new and largely unexplored interaction space. We investigate characteristics of the various skin-specific input modalities, analyze what kinds of gestures are performed on skin, and study what are preferred input locations. Our main findings show that (1) users intuitively leverage the properties of skin for a wide range of more expressive commands than on conventional touch surfaces; (2) established multi-touch gestures can be transferred to on-skin input; (3) physically uncomfortable modalities are deliberately used for irreversible commands and expressing negative emotions; and (4) the forearm and the hand are the most preferred locations on the upper limb for on-skin input. We detail on users' mental models and contribute a first consolidated set of on-skin gestures. Our findings provide guidance for developers of future sensors as well as for designers of future applications of on-skin input.

Author Keywords
Mobile computing; on-skin input; touch input; skin gestures; deformable surface; elicitation study.

ACM Classification Keywords
H.5.2. User-Interfaces: User-centered design

INTRODUCTION
An emerging stream of research proposes skin as an input surface for mobile computing [3, 6, 7, 8, 9, 10, 19, 23]. Miniaturization of electronic components enables increasingly small mobile devices, e.g. smart watches and head-mounted displays. This generates new challenges for input, since these devices tend to offer too little surface area for effective touch input. Skin provides a large input surface, which is most often easy to reach and to interact on. Therefore skin has great potential to act as a companion surface for mobile devices.

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However, skin is fundamentally different from conventional, off-body touch surfaces. As skin is stretchable, 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, for instance more varied gestures. Moreover, interaction on skin has a strong personal and strong emotional component [12, 13], enabling a more personal way of interaction. In addition, since the physiological properties of skin vary across body locations, input location is likely to be very influential – even more as people have different mental associations with different parts of their body.

This opens up a new interaction space, which is largely unexplored. We aim to contribute to the systematic understanding of skin as an input modality and of its specific capabilities. To start with, we focus on input on the upper limb (i.e. upper arm, forearm, hand and fingers), for this is the most frequently used location in previous work [3, 6, 7, 8, 9, 10, 19, 23, 24] and has been shown to have high social acceptance [30].

This paper contributes results from the first study on multi-modal on-skin input. It empirically addresses on-skin input from three main perspectives, which impact immediate usability as well as the design of future sensors and applications:

- What are characteristics of skin-specific input *modalities*, and 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 multi-modal skin input?

The study followed an elicitation methodology similar to Wobbrock et al. [31]. This approach has proven successful in prior work on a range of novel interfaces [18, 31] for providing "insights into users' mental models" and "implications for technology and UI design" [31]. 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.

The main findings and implications of our study are:

- Participants intuitively performed skin-specific gestures, leveraging physical affordances and the richer expressiveness of skin, and taking 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 input.
- Physical discomfort was explicitly desired for some types of commands. Participants performed physically uncomfortable gestures for irreversible actions, to avoid accidental input, and for expressing negative emotions.
- Half of all user-defined gestures 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 [3, 6, 7, 8, 9, 10, 19, 23, 24].
- To provide guidance for designers, we derived a first user-defined set of skin-specific gestures. This comprises skin-specific alternatives for conventional gestures as well as gestures for interpersonal communication and expression of emotional state.

These findings provide guidance for researchers and practitioners in developing future sensors as well as in designing novel interaction techniques and applications for on-skin input.

BACKGROUND AND RELATED WORK

Skin is the largest human organ. Human skin is composed of two layers: The outer layer is the epidermis, which forms the boundary between the body and its environment. The inner layer, the dermis, contains tear-resistant and flexible cells and comprises most sensory cells of the skin [5]. These cells are able to detect pressure, touch, vibration, temperature and pain and therefore allow for sensing of expressive tactile cues. Their density varies on body locations; it ranges from rather low density, e.g. on the back, to a very high density on the palms and fingers.

Prior work has suggested skin as an input surface for applications in mobile computing. On-skin input was proposed for controlling imaginary interfaces [6, 7], i.e. devices that do not provide any visual output. It was also proposed as a means of input for body-worn projectors [8, 9, 10, 21] and external displays [3, 6, 7]. Likewise, it could be used as input for mobile devices that are in the pocket [6, 7], for interacting with content on a head-mounted display or on a smart watch. Our empirical study results inform these application scenarios.

Empirical Studies of On-Skin Input

Only little previous work has empirically investigated input on skin, mostly through pointing studies.

Wagner et al. [30] introduced a body-centric design space to describe, classify and compare different multi-surface interaction techniques. The authors investigated pointing performance and user preferences of touching different body locations. Touching the upper limb was found to have high social acceptance and was rated positively by the participants. Mean pointing time was faster than on locations on the lower body, but slower than on the torso. Other pointing studies revealed that people are able to distinguish a maximum of eight to ten different locations on their forearm without or with visual cues [10, 19].

Findings of studies on palm-based imaginary interfaces showed 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 [6]. A further study revealed that when users are blindfolded, tactile cues can replace visual cues for precise pointing on imaginary interface elements [7].

All these previous studies investigated only touch input, i.e. pointing and dragging. However, studies of interpersonal touch highlighted that people can distinguish much more varied forms of touch [15]. Hertenstein et al. showed that blindfolded people are able to recognize the emotional expression of another person through touch alone [12, 13].

These findings, and generally the richness of tactile sensing, inspired us to investigate on-skin input beyond simple touch. In contrast to previous work on skin input, we study how users interact with a broader set of skin-specific input modalities. Furthermore, this is the first study investigating what gestures users perform on their skin for controlling electronic devices.

Sensor Hardware

Previous work has presented promising non-invasive solutions for sensing of on-skin input. Some sensors are a flexible, skin-like overlay that is worn as an additional layer on top of skin; other work captures input on textiles [16] or on the surface of robots [20]. In the following, we are focusing on input on bare skin, as this retains the natural feeling of interacting on skin and preserves full tactile feedback. However, advances in technology might eventually result in thin overlays, which have very similar physical properties as the underlying skin and do not interfere with tactile feedback.

One class of sensors that do not interfere with tactile feedback relies on optical capture of input by using body-worn RGB cameras [21, 29] IR cameras [17], or depth-sensors [8, 9]. This supports real-time capture of single- or multi-touch input on skin. However, to our knowledge, sensing of further input modalities than touch has not been investigated yet. Problems of camera-based approaches involve a limited resolution of sensing, occlusion, and ambient light in mobile use cases.

A second class of sensors captures input through direct skin contact, using acoustic, optical, EMG or capacitive approaches. Such sensors can be worn as wristbands or even embedded into smart watches. Skinput senses the location of tapping on the skin through acoustic transmission and reflection within skin and bones [10]. Mujibiya et al. used ultrasound propagation through the forearm to detect continuous touch with and without pressure with an augmented finger [22]. Other work proposed sensing skin deformation on the forearm using two armbands with multiple infrared-reflective sensors [23]. Capacitive detection of in-air gestures [26] or EMG measurement [27] of interactions that are performed with the touching hand might allow for sensing more expressive input. On the long run, sensors might even be implanted, which however raises questions about user acceptance [14].

METHODOLOGY

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 1. It was derived from established modalities of conventional touch interfaces and from results of studies on the biomechanics of skin [1, 11]. 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 [3, 6, 7, 8, 9, 10, 19, 24, 26, 27], it is socially acceptable for input [30], 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 (Fig. 2), which differ in their range of motion, their flexibility, and their boniness. We excluded the shoulder, as this is typically covered by clothing.

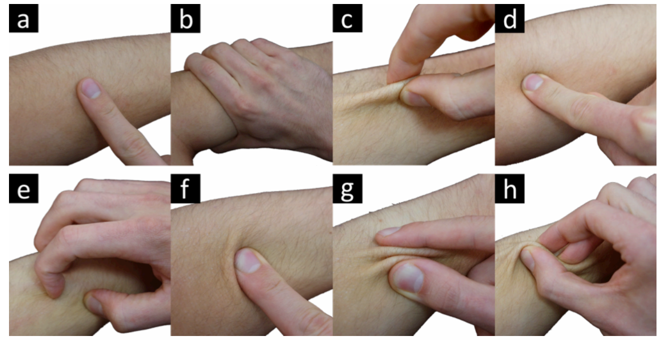

Figure 1: Input modalities: (a) touch, (b) grab, (c) pull, (d) press, (e) scratch, (f) shear, (g) squeeze and (h) twist.

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 related work section), 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 behavior [18, 31]. 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 3 gives an overview of all referents. We selected referents from prior work [18, 31] and added standard commands for

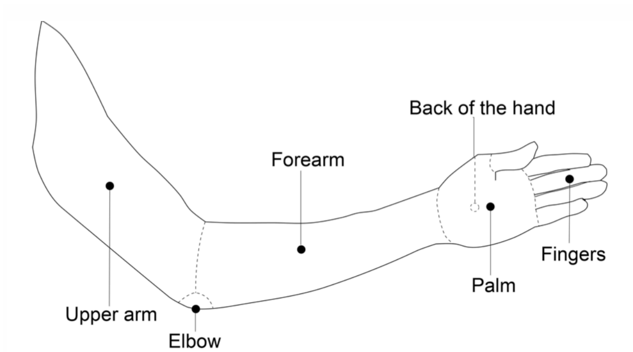

Figure 2: Locations on the upper limb.

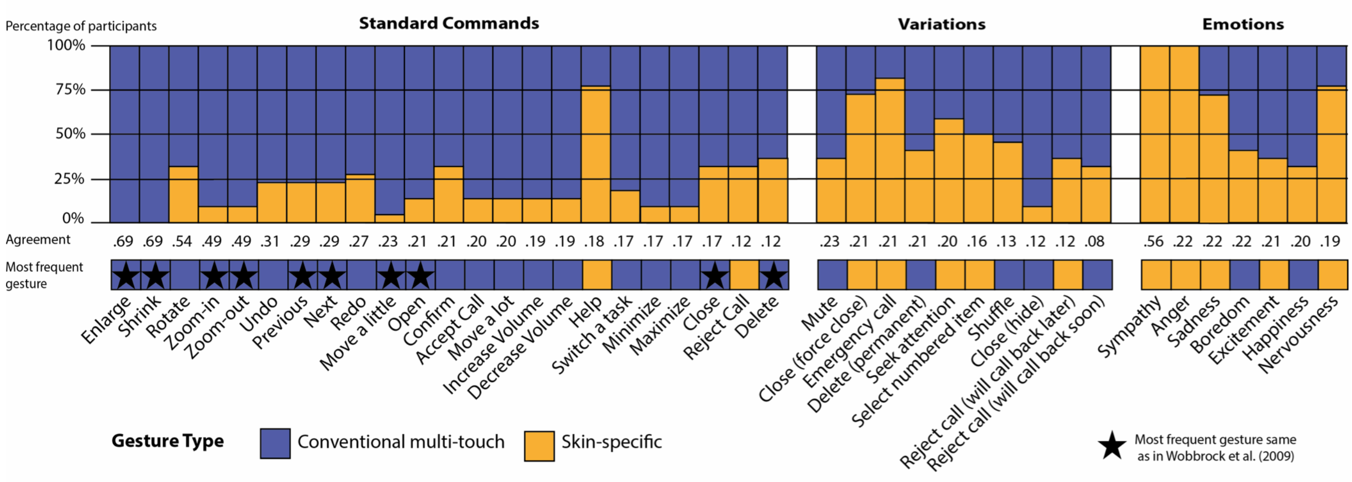

Figure 3: Overview of user-defined gestures.

mobile scenarios and variations for some referents (e.g. deleting temporarily vs. deleting permanently) to analyze how more subtle differences influence on-skin input. Inspired by the human ability to express emotions through touch [12, 13], we added a set of emotional expressions covering all four main classes on Schacter's two-dimensional spectrum of emotions [28]. 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 [25], 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 1 on page 8), 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 1).

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, 1056 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 [4] 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.

RESULTS

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.

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. The Cohen kappa coefficient of the inter-rater agreement was 0.746, indicating a substantial to excellent agreement on the definition.

Figure 3 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 as defined by [31]. Our scores are comparable with those in prior work [18, 31] 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 ($F_{(2, 63)} = 39.68$; $p < 0.05$). 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 4a 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, followed by twisting.

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 [31]. 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 below.

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 5a 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 3 participants. We opted against depicting the most frequent multi-touch gestures, since these were in-line with the findings reported in [31].

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 5b shows a conflict-free user-defined gesture set for all emotional expressions. For each expression, it contains the most frequently performed gesture. Following [31], 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.

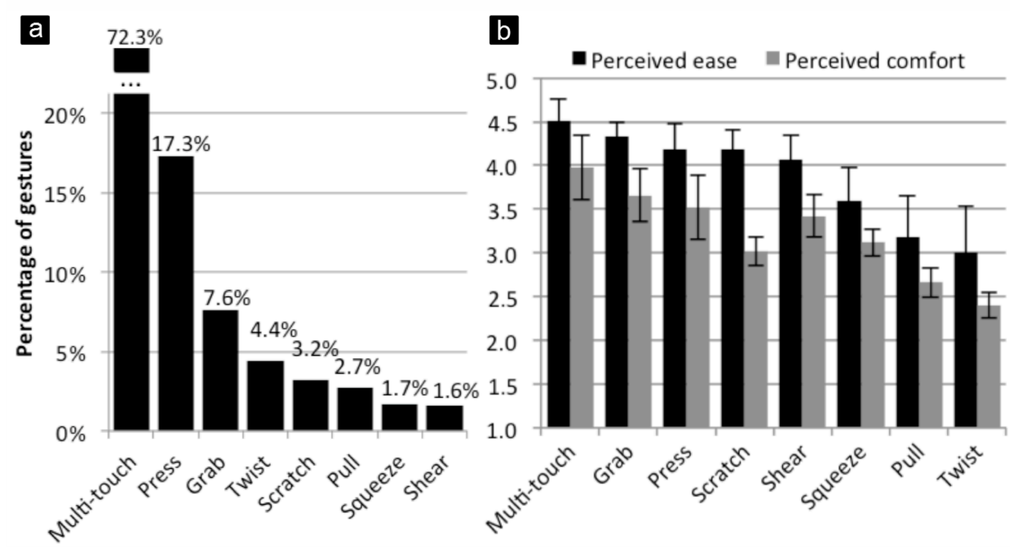

Figure 4: Input Modalities: (a) modalities used in the user-defined gestures , (b) aggregated means and 95% confidence intervals of perceived ease and comfort.

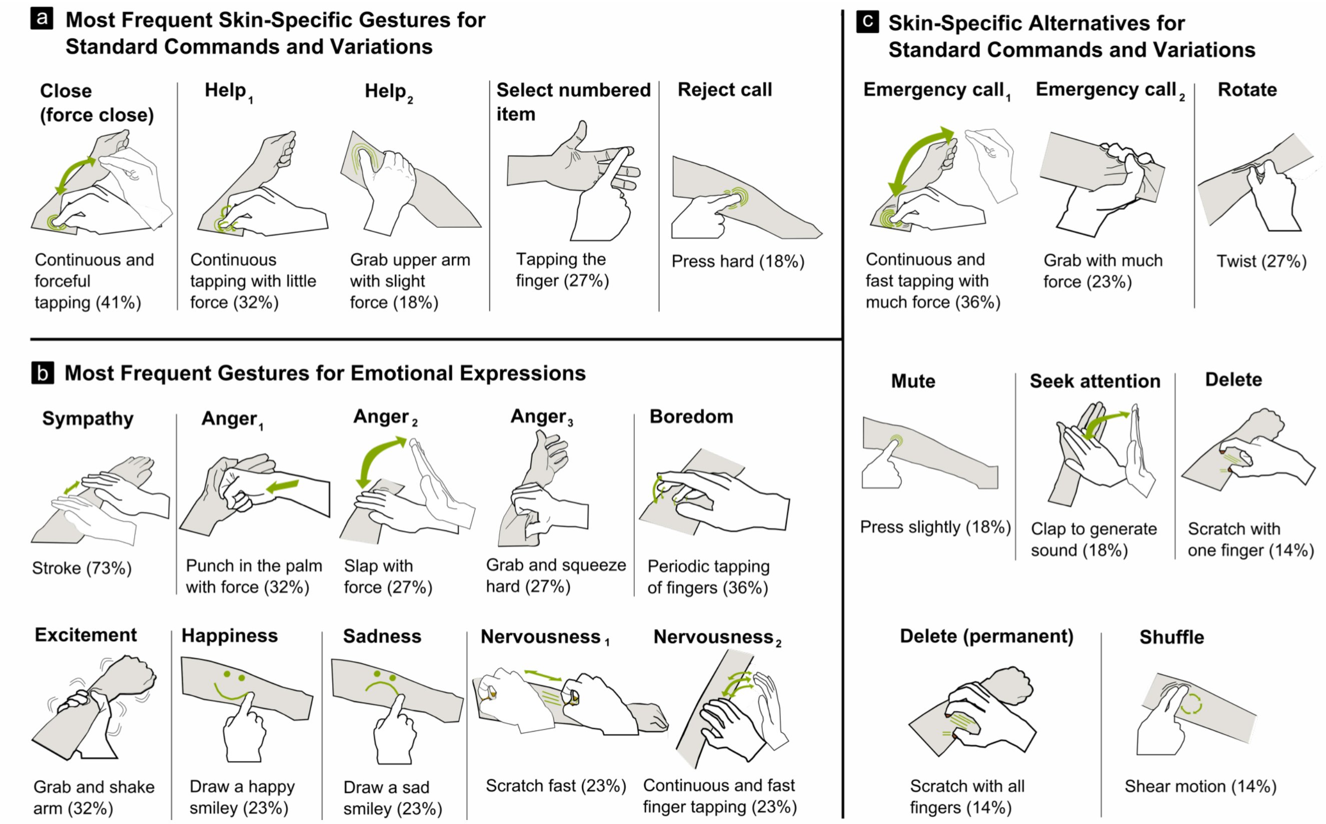

Figure 5. User-defined set of skin-specific gestures.

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.

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.

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.

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 (Fig. 1) performed on six different locations (Fig. 2) 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 4b.

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 Fig. 4a).

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.

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 [2].

Input Locations

All three tasks allowed us to investigate characteristics of input locations on the upper limb. Figure 6a shows the locations where user-defined gestures were performed. Half of all gestures were performed on the forearm. Also back of the hand and the palm were frequently used location, while the upper arm and elbow were rarely used.

Figure 6b 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 Fig. 6a, 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 Fig. 6a. 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].

Meaning of Locations

Ordered Arrangements. For all three ordering criteria (frequency of use, importance, liking) we found two mutually contradicting concepts: The majority of participants (see Table 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] or *"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 exam. It's possible to hide things there"* [P2]. This finding lends empirical support to prior research on visibility on forearm-worn displays [24].

Positive vs. Negative. The palm tended to be associated with positive actions, while the back of the hand was asso-

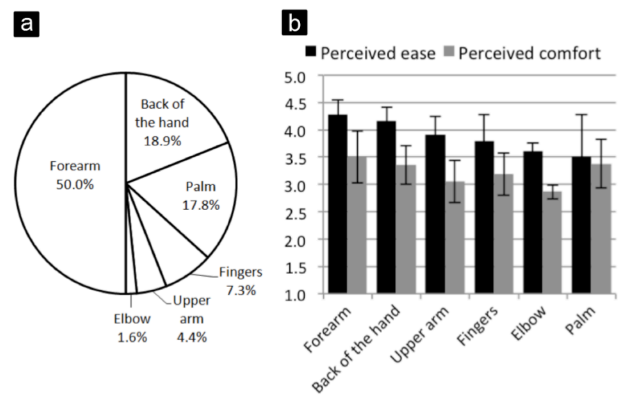

Figure 6: (a) Locations of user-defined gestures, (b) means and 95% confidence intervals of perceived ease and comfort.

ciated with negative actions. *"For me, the palm is more positive"* [P17]. The gesture for 'accept a 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 [24]. 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 [31], but accounts for the different input location.

DESIGN IMPLICATIONS

Based on the above findings, we derive the following implications for on-skin input. These provide guidance to developers of future on-skin sensors and to interface designers.

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.

Input	Preferred Locations	Order	Concept
Handwriting	Palm (59%)	Frequency	Close to the hand (86% of participants)
Keyboard	Forearm (82%)	Importance	Close to the hand (64% of participants)
Numpad	Palm (45%)	Liking	Close to the hand (68% of participants)
Sketching	Palm (41%) Forearm (41%)	Privacy	Private on inner side; public on outer (all)
Touchpad	Palm (45%) Back of the hand (36%)		

Table 1: Non-gestural input and orders of Task 3 and their most preferred locations.

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 (Fig. 5a+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 (Fig. 5b). 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 [8, 9]. 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 Fig. 5).

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 [23] or by a high accuracy depth camera that performs a 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, imaginary interface [6, 7]). This also comprises controlling a *head-mounted display* or an *external display* that provide visual output (e.g. public display or TV [3]).

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.

Smart watches: Our results show that on-skin input is most compatible with smart watches 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 smart watch. 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 [8, 9, 10]. 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 Fig. 5b). These might be perceived as being too aggressive if they are performed on a photo or live video of another person.

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 [16] 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.

CONCLUSION AND FUTURE WORK

This paper contributed findings from the first study of multi-modal skin input and derived implications for the development of future sensors and the design of future interaction techniques and applications. Our findings open up several important avenues for future research. Empirical studies should investigate the performance of skin-specific input modalities, explore user preference for a wider range of emotions and interpersonal commands and study cultural effects. Future sensors for on-skin input would benefit from integrating multi-touch with pressure sensing, since this would allow for sensing the largest part of the skin-specific gestures that were performed in our study. Future applications can make use of the proposed gesture set to interact in a more personal and more expressive way with electronic devices.

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