Implications of Location and Touch for On-Body Projected Interfaces

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ABSTRACT
Very recently, there has been a perfect storm of technical advances that has culminated in the emergence of a new interaction modality: on-body projected interfaces. Such systems enable the wearer to use their body as an input and output platform with interactive graphics. Projects such as PALMbit and Skinput sought to answer the initial and fundamental question: whether or not on-body projected interfaces were technologically possible. Although considerable technical work remains, we believe it is important to begin shifting the question away from *how* and *what*, and towards *where,* and ultimately *why*. These are the class of questions that inform the design of next generation systems. To better understand and explore this expansive space, we employed a mixed-methods research process involving more than two thousand individuals. This started with high-resolution, but low-detail crowdsourced data. We then combined this with rich, expert interviews, exploring aspects ranging from aesthetics to kinesthetics. The results of this structured exploration, point the way towards more comfortable, efficacious, and enjoyable on-body user experiences.

Author Keywords: On-body computing; touch interaction; projected interfaces; wearable; always-available input.

ACM Classification Keywords: H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION
Computing has evolved repeatedly and dramatically in its short history. In the 1980's, the mainframe era transitioned to a focus on desktop computers. The latter brought computational power much closer to users, enabling a high level of customization and computational freedom, and sparked the "personal computer" revolution. Today, mobile computers have moved to the forefront, bringing computation ever closer to the user—into our pockets and bags.

In this paper, we discuss an emergent shift in computing: from mobile devices we carry to using the human body as an interactive platform (Figure 1). By moving the power of information, communication, and computation right onto the skin, researchers hope to reduce interactive viscosity in the same way mobile computers did relative to their desktop counterparts. This evolution brings significant new challenges not only in sensing, but also interaction design.

To date, research into on-body projected interfaces has primarily focused on the fundamental question of whether or not it was technologically possible. Although considerable work remains, these systems are no longer artifacts of science fiction—prototypes have been successfully demonstrated and tested on hundreds of people [11,14]. Our aim is to begin shifting the question away from *how*, and towards *where*. This is the class of question that informs the design of future systems and validates some design decisions used in current systems that were based on anecdotal evidence.

To understand this expansive space, we employed a two-part, mixed-methods exploratory process. Participants from a variety of backgrounds were asked to reflect on their openness to interacting with touch interfaces projected onto various parts of their own bodies, and also touching interfaces projected onto others. Our investigations started with high spatial resolution, but low detail crowdsourced data. We then complimented this model with low spatial resolution, but high-detail qualitative feedback from a diverse set of experts, including a tattoo artist, massage therapist, and dance instructor. The results of this structured exploration reveal both limitations and opportunities, which point the way towards for more comfortable, efficacious, and enjoyable on-body user experiences.

RELATED WORK
Our work draws upon two distinct literatures. Foremost are on-body systems that have demonstrated the feasibility and utility of bringing interaction onto the body. These systems inspired the central question of this paper: if we could have interfaces on the body, *where* should they appear? The second body of work broadly relates to embodied interfaces and social dimensions of touch, which heavily informs our explorations. Questions surrounding human form, movement and touch have existed for millennia, and as such, we can highlight only a notable subset of related work.

Embodied Interfaces
Touch is unique among human senses in that it operates through direct contact with the physical world. On-body projected interfaces can unify cognition and bodily action, increasing agency [3] and offering tremendous potential to outperform other interaction modalities, since the physical world being touched is the users' own body [30,38,40]. As the col-

DIS '14, June 21 - 25 2014, Vancouver, BC, Canada

ACM 978-1-4503-2902-6/14/06…$15.00.
http://dx.doi.org/10.1145/2598510.2598587

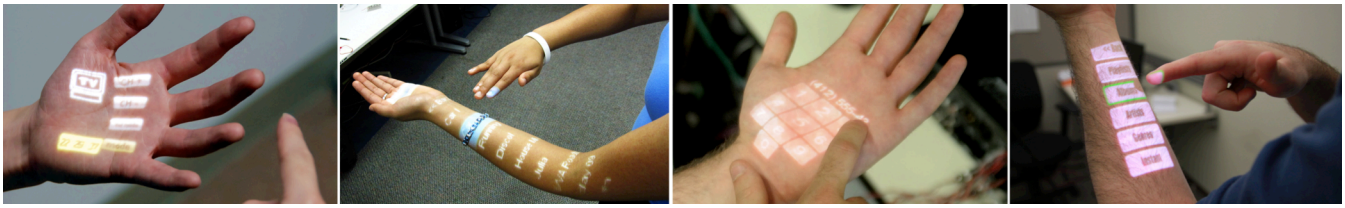

Figure 1. Example On-Body Interfaces. From left to right: PALMbit [41], Armura [13], Skinput [14], and OmniTouch [11].

loquialism "like the back of your hand" suggests, we are intimately familiar with our own bodies. Because of this, we develop finely tuned muscle memory and hand-eye coordination. Further, proprioception allows us to rapidly and accurately position our body, limbs, and digits, without tactile feedback and even with our eyes closed [8,32,40]. Moreover, the body has dozens of additional degrees of freedom that could be captured for interactive purposes [13]. The rise of tangible computing has demonstrated that object-specific manipulations such as shaking, squeezing and rotating physical artifacts, align embodiment with physical representation and embeddedness in space [19].

On Body Input

A number of approaches have been proposed to enable on-body input. The most straightforward is to take conventional computing elements and wear them on the body. Iconic examples include a one-handed keyboard [23] and a wrist-bound touchpad [36]. Another approach involves input devices built into a form considered to be part of one's clothing [2,24,31], or even to instrument the body more directly. For example, glove- and fingertip-based input systems [34] can capture a great deal of expressivity, though they are cumbersome and disruptive to tactile sensation. Gustafson et al. [10] demonstrated instrumentation-free sensing on the palm using computer vision. There has also been work at the intersection of computer input and biosignals (e.g., EMG [33] and bio-acoustics [4]). Most recently, Weigel et al. demonstrated skin gestures that can utilize input dimensions such as pulling, pressing and squeezing [39].

On-Body Projection

Although many projects have employed handheld projectors, few have taken advantage of the body as a projection surface. Unsurprisingly, the art community was among the first to embrace the fusion of the human form with projected digital media. Examples include the opening sequence to Guy Hamilton's "Goldfinger" (1964) and Peter Greenway's "The Pillow Book" (1996). Barnett [1] provides a summary of many of these artistic efforts. On-body projections have also seen interest in the medical domain, for example, to assist with surgical procedures [9].

On Body Interfaces

Rarest and most recent are systems that attempt both input and graphical output on the body (Figure 1). It is this unique combination that defines *On-Body Projected Interfaces*, and enables a range of sophisticated interactions and applications not possible with input or output alone. One of the earliest systems, PALMbit [41], uses a shoulder-worn projector and camera. Interfaces are projected onto the palm of the user, which is actively tracked in real-time without the need for markers, though a special hand pose is required. Users input by pressing one of the five fingers (a la "buttons"). SixthSense [28] is also computer vision powered; colored markers worn on the fingers allow the hands to be tracked for input. OmniTouch [11] is a shoulder-worn, depth-sensing and projection system that enables interactive multi-touch applications on everyday surfaces, including the body. Skinput used bio-acoustic fingerprinting to detect and localize finger taps on the skin [14]. Finally, rather than being worn and mobile, systems such as Armura [13] are fixed infrastructure that allow anyone residing in their field of view to take advantage of projected on-body interfaces. Neither system enabled direct touch on the body, instead relying on the position and movement of the limbs for input.

Social Dimensions of On-Body Touch

Because on-body computing systems require direct interaction with the body, their design necessitates an examination of the social acceptability of touch. The importance of touch is widely acknowledged in childhood development (honing essential motor skills, spatial and emotional perception, and psychological and physical health [6,15,29]) and also adulthood, given its importance in interpersonal communication.

Recent work has examined the distinct emotional signals that are conveyed through touch and how touch enhances the multimodal perception of emotion [21,35]. Studies of identification of emotion from being touched by an unseen stranger on the arm, or when watching someone else being touched on the arm, demonstrate that a tactile modality can accurately signal at least six emotions to a degree comparable to facial and vocal communication [16].

One of the most comprehensive studies on the meanings people assign to touch was a study by Jones and Yarbrough [20]. Data from 37 participant observers trained to directly notate touch events in which they were involved demonstrated the variety of precise cultural meanings communicated by touch. For every social touch event they experienced over three days, participants immediately recorded: who initiated it; the number and location of body parts that came into contact; whose space the encounter occurred in; who said anything and the timing of the verbalization in relation to the touch; the participant's interpretation of the meaning of the touch; and other relevant data.

Nearly 1500 touches were collected and analyzed, revealing 12 distinct categories of meaning for touch: support, appreciation, inclusion, sexual interest or intent, affection, playful affection, playful aggression, compliance, attention-getting, announcing a response, greetings, and departure. They also

identified two general regions of the body: *non-vulnerable body parts*, including hands, arms, shoulders, and upper back, and *vulnerable body parts*, comprising everywhere else—the head, neck, torso, lower back, buttocks, legs, and feet. They observed that vulnerable parts were touched in *close relationships*, while non-vulnerable parts were socially available for *others to touch*.

Perhaps the most significant aspect of this study is the finding that interpersonal touch has specific and widely ranging symbolic meanings in adult communication, and that contextual factors (such as verbal and nonverbal behaviors and relational and situational factors) are critical to the meanings of touch events. For on-body interfaces to seamlessly integrate into real-world use, they will need to understand and leverage these variable social contexts in adaptive ways.

Recent work examining some of the contextual nuances of interpersonal touch from disciplines such as cognitive and social psychology, neuroscience, and cultural anthropology, demonstrates that it appears capable of powerfully affecting people's behavior. Gallace and Spence [7] review work on how even casual interpersonal touch can powerfully affect people's attitudes towards a particular service, their compliance with requests, and their degree of bonding with others.

However, in many social contexts, interpersonal touch is actively discouraged for cultural and legal reasons, norms that will need to be carefully considered by on-body interface designers. Some guidance may be found in a survey of nearly 500 college students [37] of beliefs about where it is acceptable to touch and be touched by other students in casual social interactions with the intent of informing college sexual harassment and health policies. A hierarchical cluster analysis was used to form *touch zones* (Public, Discretionary, and Private) by gender showing the ratio of acceptability of touching a zone in each condition. Yet while this approach classifies where students believe it is acceptable to touch and be touched in casual social interactions, such studies do not address the real-time question of why such touching may or may not be contextually appropriate.

One possible means of guiding the acceptance of interpersonal touch is through the design of embodied interfaces that facilitate social interaction. In a project titled Mediated Body, Hobye and Löwgren [17] present an experimental interactive performance that uses a body suit and audio feedback to justify bare-skin touch between strangers. This paradigm is a striking example of how mediated environments can provide open-ended prompts for social interaction that can extend across bodies. Such mixed-reality interfaces heighten the potential for interpersonal communication, and indicate a largely untapped area of research.

In general, on-body interactions provide the potential for heightened sensory perception, and consequently, associated improvements in emotional awareness and human-centered creativity [5,22,27]. Although research into the social implications of on-body interfaces is clearly in an early stage, our aim with this project is to provide guidance on how such development might best proceed.

CROWDSOURCING A BASELINE MODEL

Before we could begin asking questions about *why* locations were good or bad for on-body projected interfaces, we first had to know *where.* Thus, our first step was to build a baseline model for the appropriateness of locations across the human body. Of course, there are a multitude of biological, personal and cultural factors that influence this model, including body image issues, greeting customs, and musculoskeletal constraints. To build a model that illuminated generalizable recommendations, it was important to solicit input from a wide spectrum of people. To achieve this, we designed a task for Amazon's Mechanical Turk. The population of participants (workers) is a reasonable proxy for the population at large (see [32] for more discussion).

Developing a Set of Poses

The human body can form an almost limitless set of possible poses. In these different poses, the appropriateness of on-body projected interfaces change, due to factors such as physical and visual accessibility [12]. In response, we felt it was important to investigate a set of poses, such that these differences (potentially opportunities) could be explored. Through five hours of informal observations at a cafeteria, coffee shop and library, a set of seven commonplace poses was decided upon. In addition to standing, there were six varieties of sitting: legs together, reclined and legs together, legs apart, legs crossed at knee, legs crossed ankle-to-knee, and crossed legged on floor (Figure 3). A vast majority of typical peoples' days are spent in these various poses [26].

Procedure

After filling out basic demographics information, participants viewed a thirty second, silent video montage of projected on-body interfaces from three arm- and hand-centric on-body systems [11,13,14]. A numerical code appearing briefly in the middle of the video was necessary to continue. We first we considered using storyboards and mocked-up photos. However, piloting proved useful in determining that the inclusion of a video was absolutely necessary. On-body projected interfaces are something most people have never encountered. A video very quickly and accurately conveyed the main idea in a way that text and images could not.

Participants were then presented with a randomly selected black silhouette, depicting one of the seven poses described in the previous section. A single small green dot was superimposed onto a random body location (Figure 2, left). If visualized all at once, these dots would form a regular grid covering the silhouette, spaced apart by ten pixels both horizontally and vertically (Figure 2, right). As an additional postural cue, a small inset image depicted a stick figure in side profile in the same pose.

Participants were told to "imagine this silhouette is your body" and also to "imagine you are in a public place and there is an interface projected onto the location of the green dot." Below the silhouette, a single question was asked. Participants were randomly assigned to one of four conditions upon starting the experiment, each featuring a different question, found in Table 1. Participants answered this ques-

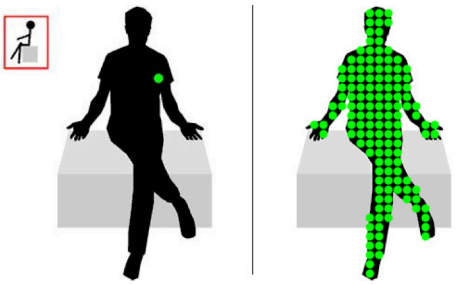

Figure 2. Left: an example silhouette and dot location. Right: Visualization of all dot locations if rendered together (136 total for this pose). Across all 7 poses (Figure 4) there were 952 dots.

tion using a five point Likert scale: 1) very uncomfortable, 2) uncomfortable, 3) neither uncomfortable nor comfortable, 4) comfortable, and 5) very comfortable. In total, participants entered responses for 20 silhouettes, each with a random pose and dot location.

We chose to exclude the back of the body. Not only would this have doubled the number of points we needed to test, but more importantly, we found the back confused people in piloting, as it is not a surface that can be practically used (hard to reach, hard to see). Additionally, the decision to use the somewhat indistinct scale of "comfort" was difficult, but deliberate. Of the many adjectives we considered, comfort best captured the multi-dimensional and highly personal nature of touch [16,25,40]. In piloting, users interpreted "comfort" in both the physical sense and also with respect to social ease – paramount aspects of our exploration. Likewise, we also elected to use the somewhat indistinct phrase of "someone you are close with" (used successfully in [20]), as there are many different types of relationships that do not necessarily follow a linear progression of intimacy. These decisions were calculated experimental compromises aimed to control combinatory explosion. Nonetheless, our experiment captures 56 conditions, covering what we believed were the most important factors for a baseline exploration: pose (7), gender (2), touching vs. looking (2), self vs. others touching (2). Further, each condition was comprised of approximately 150 body locations to be rated.

Finally, we instituted two reliability checks to ensure a high level of answer integrity. First, questions 1 and 10 were repeated in the set of 20. A participant's data was dropped entirely if answer pairs differed by more than one Likert point. Further, participants with very low answer variance were also dropped (e.g., all 3's).

Participants

2,496 Mechanical Turk workers completed the study for $0.25. Participation was limited to those residing in the US; although multi-cultural, results from this population should not be assumed to hold across cultures. Data from 484 participants was dropped as per the quality check noted previously (a proportion inline with other mturk-based studies). Subsequent discussion is based on data from the remaining 2,012 participants (mean age 27.0, SD=9.1, 63% male). 84.8% reported being right-handed, 12.8% left-handed, and 2.4% ambidextrous, matching the general population [18].

	Self	Others
Touching	*How would you feel about **touching** an interface projected on this location with your fingers?*	*How would you feel about someone you are close with **touching** an interface projected on this location with his or her fingers?*
Looking	*How would you feel about **looking** at an interface projected on this location?*	*How would you feel about someone you are close with **looking** at an interface projected on this location?*

Table 1. Participants were assigned to one of four question conditions, exploring self vs. others and touching vs. looking. Bold and underline used to only here to highlight differences.

Generating Heatmaps

Our participants produced 36,216 responses to the 952 silhouetted interface location questions. Within each question condition (Table 1), we ensured that each body location had no fewer than 5 responses – this was important to reduce noise in our models (the average location had 13.2 responses). Combining all four conditions, each location had no fewer than 23 responses (mean 52.7). As noted before, locations formed a grid with ten-pixel spacing (Figure 2). To produce filled heatmaps, we used bilinear interpolation (see Table 2 for color scale). Figure 3 displays general models (i.e., combing condition, gender, etc.) for the seven poses.

EXPERT INTERVIEWS

The crowdsourced heatmaps provided a high resolution, tip-to-toe visualization of appropriateness. However, standing alone, they could only offer a thin shell of information: it was easy to identify *where*, but not *why* a body location was well suited to on-body projected interfaces. Also missing were special considerations, for example, transient factors that might enable a body surface for a passing moment. Even before the heatmaps were generated, we knew that some areas were obviously inappropriate for interactive use, such as the groin, and did not require extensive study. However, we knew much less about other areas of the bodies – those with more nuances - including the shoulders, thighs, abdomen, legs, and upper arms. Thus, to fill out our *where* model with an equally rich understanding of *why,* we also conducted in-depth interviewers with experts.

Expert Participants

Unfortunately, due to the nascence of the field, there are no on-body interface experts. Thus, we solicited experts from related backgrounds, which broadly covered three areas of interest: 1) kinesiology and position, 2) ergonomics and physical comfort, and 3) aesthetics and social aspects. We found that most of the experts we interviewed touched other people as part of their work. This allowed our experts to not only comment professionally and personally on aspects of touch, but also provide considerable insight into how others

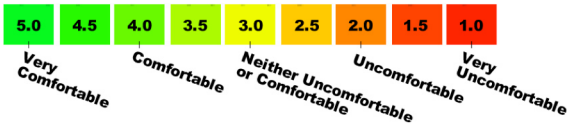

Table 2. Color scale used for the crowdsourced heatmaps.

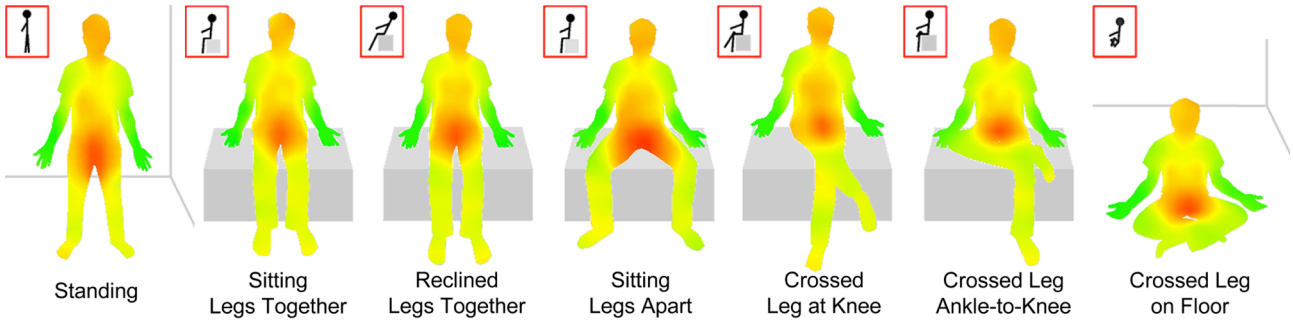

Figure 3. The seven poses included in our exploration. Heatmaps superimposed here are combined models (all study factors).

feel and react to being touched on different parts of their bodies. Brief descriptions of our ten experts follow, including abbreviations used subsequently:

(BM) *Boutique Manager* - Female, 24. BA in Fashion Design and Merchandising. Three years experience in corporate retail, and three years managing a boutique. Works daily with clients; understands how clothes fit on the body and how clothing design can draw attention or minimize different parts of the body.

(DI) *Dance Instructor* - Female, 28. Has been dancing since age 13; four years experience as dance instructor. Specializes in west coast swing, a social dance, requiring regular and fairly intimate interpersonal touch. Extensive professional observations.

(AD) *Accessory Designer* - Female, 49. Started work in bridal shop making accessories. Now has almost 20 years experience as accessory designer; costume design and seamstressing on the side. Deep understanding of how accessories can highlight areas of the body and how to design such worn accessories.

(CP) *Chiropractor* - Male, 72. "Touch is what I do." Has a deep understanding of where and why parts of the body hurt and how people react to being touched. 46 years experience; owns practice.

(JM) *Jewelry and Metalsmith* - Female, 35. BFA and MFA. Instructor and practitioner for 12 years. Knowledge of how to design confortable and aesthetic artifacts that are worn on the body.

(YI) *Yoga Instructor* - Female, 29. Three years experience as instructor. Deep awareness of body form and position issues.

(MT) *Massage Therapist* - Female, 26. Has completed 700+ hours of massage therapy courses. Licensed and practicing for almost three years. Considerable professional experience touching others and observing reactions.

(ME) *Tattoo Parlor Owner and Body Modification Enthusiast* - Female, 33. Has tattoos over much of her body, including face, as well as stretched ears, lip piercings, and microdermal implants. Knowledge of where augmentation/instrumentation is most practical, comfortable and fashionable.

(TA) *Tattoo Artist* - Male, 41. Fifteen years professional experience; has worked on thousands of tattoos. Extensive career touching others, understanding skin sensitivity, and overlaying graphics onto the skin.

(EC) *Ergonomics Compliance Manager* - Male, 70. Certified ergonomic compliance manager, certified safety manager, and an OSHA-authorized trainer. 18 years experience. Extensive hands-on knowledge of injuries relating to technology use and general musculoskeletal issues.

Procedure

Interviews lasted approximately one hour; participants were paid $40 for their time. The interviews started by discussing what their jobs involved, training or experience required, interesting professional experiences, and similar background matter. Following this general discussion, participants were shown the same silent, 30-second video montage used in the crowdsourced study. Following this, they were allowed to ask questions and comment on what they had seen. The interviewer elicited additional discussion by asking participants if they would use such a technology and also to imagine possible benefits and drawbacks, especially in relation to current mobile devices.

Next, participants were presented with an outlined silhouette of a person standing. They were told to imagine this was themselves, and that on-body interfaces like they had seen in the video could appear anywhere on their body. Three marker pens were made available: green for locations that were most appropriate, red for poor locations, and blue for locations that were somewhere in between, or neutral. Participants were told to color the silhouette and think aloud during the process, commenting both personally and from their professional experiences. This exercise (see Figure 4 for examples) proved highly effective in getting participants to systemically consider all parts of the body, and vocalize the multitude of reasons why different areas would be good and/or bad. Frequently, participants touched and reconfigured their own bodies to help with their assessment.

After completing the standing silhouette, participants duplicated this exercise for the remaining six poses. It became clear after the first two interviews that appropriateness for much of the body remained unchanged across poses, the torso in particular (reflected in Figure 3). Thus, participants were told to focus primarily on differences from the standing pose, which was left on the table for comparison.

After completing all seven poses, participants were once again presented with an unmarked, fresh silhouette of a person standing. Participants were told to imagine again this was their body, however this time, instead of touching

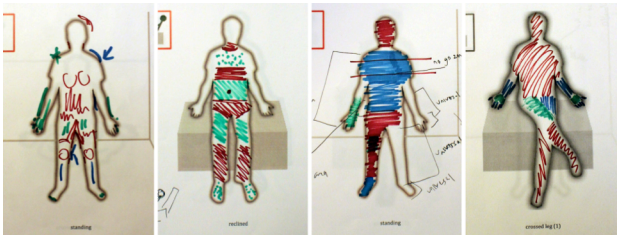

Figure 4. Four example silhouettes "filled in" by experts during the think aloud exercise. Three pens were provided: green for 'good' places, red for 'bad', and blue for neutral.

themselves, it was someone close to them touching. When appropriate, this was interleaved with discussion about how they would feel if a perfect stranger asked to use their body for an interaction (e.g., to call a taxi). After the interviews were completed, they were transcribed, coded and synthesized using affinity diagrams to identify common themes.

DISCUSSION AND DESIGN RECOMMENDATIONS

Our crowdsourced heatmaps provided a high spatial resolution view of appropriateness. However, the explanatory and descriptive power of any one location was low given the underlying Likert-style data. Conversely, our expert interviews had low spatial resolution - perhaps only ten broad areas of the body were discussed vs. 150 points. However, for these areas, we gathered rich and detailed notes. In this section, we combine these complimentary results, highlighting core issues of appropriateness across the human form. In particular, this enables us to discuss the *where* and *why* in tandem for the first time. We use a digest of quotes from our experts to bring to light key design recommendations.

We include several heatmap models to help guide and ground our discussion. Unfortunately, due to space, we could only include a small subset of our heatmaps. Breaking these out by pose, gender, age, touching vs. looking, and self vs. others yields hundreds of heatmaps, which is impossible to discuss in this context (see Open Data section). Thus, we have elected to combine results where appropriate in order to highlight key findings.

Expert Reactions

Most of the experts interviewed found the technology vision appealing, and many said they would use it today if available. Others were less enthralled, but nonetheless articulated many potential benefits. Universally noted was the immediate accessibility: "Just convenient, you're not carrying a lot of stuff, it's always there" (TA); "Access would be easier" (BM); "So easy, it's always right there" (AD); "If you need something, it's right there, you don't have to remember it" (ME); "Hands free, less to carry, its always with you" (EC).

Less apparent was that the "display takes up no space" (DI), "it's not something you have to stuff into your pocket and lug around with you" (TA) and potentially could offer even "bigger space" (CP). The potential for eyes free operation was also remarked on: "Skin is really comfortable. [Interviewer: 'as comfortable as a touch screen?'] Maybe more. Your hands are super sensitive - you can even do it without looking as much" (JM). Finally, EC noted, "I don't see [such interfaces] being a big ergonomic issue."

Visual Accessibility

Experts were fairly decisive and universal in their preferences for locations across the body. With very few exceptions, experts strongly aligned with the heatmaps. Most locations were quickly dismissed as being inappropriate, in favor of the arms and legs (discussed subsequently). The most pervasive reason to disqualify a location was visual inaccessibility. "When standing, there's not enough places on the body you can see really well" (JM). "It'd be weird to have interfaces on your legs, or body. How are you going to see it?" (AD) The head draw the obvious criticism: "[you] can't see your own head" (JM), "you'd have to look at a mirror" (TA). Similarly, the back is "inconvenient" (YI).

The front of the body is also problematic: "Chest is lot of surface area, but looking down at it, you're not going to see it all" (BM). "How can you see it? [Even reclined] you would have to crane your neck" (CP). With specific respect to the upper chest: "I can't read here." (DI). The stomach area: "wouldn't find that area that useful, and it's kinda weird" (JM); "Weird to project on the stomach" (DI).

Figure 5 shows heatmaps in a sitting pose separated by touching and looking at interfaces at one's own body. It is readily apparent the trunk of the body is considered visually inaccessible or awkward (right), with mean comfort ranges between 1.52 and 2.72 (mean 2.3). More areas, however, are physically accessible (left) by reaching with the hands.

Hands and Arms

The most favorable and universally accepted area of the body for projected touch interfaces was the arms (across all poses, mean 4.3, see Figure 3). Not surprisingly, this is where past on-body systems have focused their efforts (see e.g., Figure 1) and previous research has confirmed as the least vulnerable [20]. Among a multitude of reasons, visual and physical accessibility were the most commonly cited, matching results in [12]. "You can flip it into whatever angle you need" (BM); "Hands are most visible" (JM); "The arm - its right there!" (AD). "[Arms] are always there in front of you, you can bring them up" with visibility "similar to a book or newspaper" (EC).

Also commanding much discussion were aspects of control. "I feel like hands would be pretty intuitive… two [hands] working together" (TA). "You have a lot of control on your hand over other places" (JM). "You are used to touching things with your hands. That's how you touch [the world]" (CP). "You can feel much more small gradations in movements [on your palm]" (TA).

Pose comfort did not appear to be a significant issue. "You can tuck [the arm] in close and not support it" (TA). "Most natural is straight out like this [*palm up, forearm supinated*]… Keep it in a plane, elbow at 90 degrees." (EC). On sustaining the latter arm pose, CP noted, "I can't imagine that would be a problem for many people," even older users.

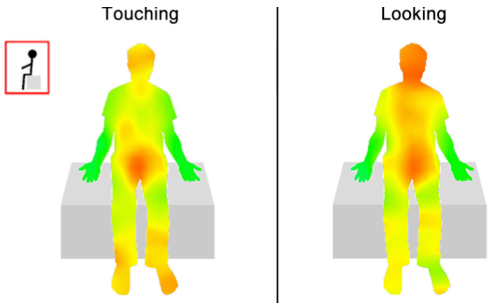

Figure 5. Heatmap models in a seated pose separated by touching and looking at interfaces on oneself.

Additionally, two experts commented that the hands could be supported by "resting arm on the thigh" (EC), or perhaps a table or armrest. "If you have a support surface, you can be kinder to your body" (DI).

These benefits did not extend above the elbow (a result also found in [39]); the upper arm was generally disliked from a visibility standpoint (see Figure 5). "It's closer to focus, and has a weirder angle" (MT); "Above the elbow, how are you going to look at it?" (CP); "Angle is kind of bad" (BM); "Forearms up to elbow. Not above, awkward posture … very close to your eyes. [Lower arms are] better from a comfort and ergonomics stand point" (EC). However, DI noted that the upper arms could serve as peripheral displays.

The second most common arm posture demonstrated was similar to how one would read a wristwatch (arm held up, elbow flexed, forearm pronated). While convenient and exposing a desirable forearm area (discussed next), it is "not something people can sustain" (EC) for extended periods. However, repeated use might mitigate this issue: "There are styles of belly dance where your arms don't go below shoulder level for half an hour. You can train to do that" (DI).

The irregularity of the hand was identified as a potential usability issue. "[Hand is better for] applications that aren't so visual… like an instagram on your hand probably wouldn't be that great," but for typing an email "it'd be fine" (TA). The "inside [of the arm] is best, no hair on it, smoother, clearer, flat. Next best is the palm, then back of arm, then back of hand" (AD). Although experts were generally positive about the inner arm, it was tempered with sensitivity issues. For example, the inner arm "skin is more sensitive to touch" (YI) as "veins and tendons are closer to the surface" (MT). Similarly, "the back of the hand… skin is thinner, has more nerve endings than forearm" (MT). The outside of the forearm drew less concern "because the skin is thicker" (YI) and less sensitive. "Better off on the outside. Poke in here [inside of arm] you could hurt someone" (CP). Overall, however, "people can usually tolerate pretty firm pressure [touches] in the arm" (MT).

Fingers were notably absent from commentary during the think aloud exercise. When prompted: "I don't really see a huge advantage from being on the fingers" (TA). Although providing a contiguous extension from the palm when together, it is not a neutral pose: "I can hold them together, but it takes some force" (EC).

Thighs and Legs

Though the response was less enthusiastic, the thighs were also frequently mentioned. They were universally appreciated as affording more room for interaction, assuming a seated pose. The "tops of your thighs ... have a lot of room" (TA), "would have more surface area, if you are reading something with longer text" (YI), and "are relatively flat" (CP) for better projection.

Using the legs as the interactive surface frees the hands, enabling bi-manual interactions. Of particular interest was the ankle-to-knee crossed-legged pose, which opens a large, contiguous and smooth surface for interaction on the calf, which is oriented perpendicular to the body. "The inside of your calf… this is funny because when you tattoo yourself … that's where you do it, because you need both hands ... and I can see that working here… hmmm, you could type [with both hands] on your leg" (TA), "like a keyboard" (EC), "the mid section of your lower leg crossed over, like a screen" (YI). This opportunity was also reflected in the heatmaps (area mean of 3.02), the highest rating of any leg region except when cross-legged on the floor.

Two of the seated poses we explored had legs that were crossed. Several experts raised ergonomic issues: "Not healthy to cross your legs… I don't like the crossed [one] where your legs are really tight, because that is bad against blood flow" (YI). EC noted that "anytime you have contact, bone to bone, but more importantly, compressed nerves, compressed blood flow" there is going to be a fatigue and comfort issue. Experts noted that people "tend to switch legs constantly" (DI) in this pose. This isn't necessarily detrimental, but does impede prolonged use. In regards to looking at such interfaces on the legs, "you'd really have to hold your neck down … after a few minutes I'd have to [*stretches neck*]… the neck and upper back will start to feel it" (EC). This was much less of an issue with the arms.

Likewise, there were points raised regarding touch sensitivity. "Almost everybody is more sensitive in the legs" (MT). In particular, "knees are very sensitive" and "shins can be tender" (CP). Experts tended to highlight the ideal location for interaction starting at the mid thigh and ending just before the knee: "[with] the length of the arm, your arm naturally goes to your knees" (MT). "Maybe halfway down the thighs, beyond that you're going to be pulling your arms back" (EC), forming an acute elbow angle and putting stress on the shoulders and upper arm. Simultaneously, this arm pose also keeps the hands away from the groin (discussed next). This preference towards the lower thigh is confirmed in the heatmaps (Figure 3).

Finally, feet (and lower legs) were quickly dismissed as practical locations for on-body projected interfaces. When discussed, they were always portrayed as being input poor. "You can use the feet for any sort of display that didn't require something else to poke at it … it's not going to be as detail oriented as you can be with your hands" (DI). "It'd be kind of far away to do anything" (TA) and "text is going to have to be larger [to see]" (DI).

Groin Considerations

In general, interaction on the "crotch would not be the most appropriate. In public, it is always a bad area" (BM). "You don't want to have to poke yourself in the crotch to hit OK" (DI). "I don't know if you'd want to be manipulating anything on your crotch, because it just looks bad. But as far as, like from a technical stand point, it's not, I don't think… if you are me, you can't even see your crotch if you are sitting down, but if you don't have a pop belly.. then.. I think that would be more of a social thing" (TA).

DI explained: “There two things that affect the crotch areas availability and sensitivity. The thing that affects availability the most is the angle between the legs and torso. If you are standing, there is more area here, and if you sit, there is less area that is accessible. The thing that affects the sensitivity is the angle between the two legs - the further your legs are spread, the more dicey it feels to be touching there” (DI). When the legs are crossed, the groin “doesn't exist as much, tucked underneath you” (BM). This effect is easily seen in the heatmaps (Figure 3): e.g., legs apart (min 1.29, mean 1.72) vs. crossed legs at knee (min 1.83, mean 2.10).

Gender and Body Image

There was a great deal of commentary on gender differences and the “politics of touch” (MT). Beyond the obviously taboo groin area, neither male nor female experts described any front-facing, reachable areas that would be totally off limits for men. On the other hand, women experts most often provided a significant list of locations that would be off-limits on the female body. “Arms, whole arms, are more universally [acceptable] for men, no matter what shape your arm is in. Women think their arms can be too skinny or too fat - men don't seem to think about it” (BM). “Women are sensitive about their legs. Some people are weird about feet. There is a whole degree of women out there that won't wear a short sleeve shirt” (AD). “[Chest] area is off limits” (DI). “I don't know many women that really like to look at their thighs and study them, because they are so critical already, or belly or breasts, like all these hot spots” (YI).

Concern stemmed primarily from drawing attention to sensitive areas. “It all really depends on what relationship you have with your body” (YI). “People who are self conscience or cautious about those part of their body wouldn't want to be touching them.. wouldn't want screens on them.” (BM) “For a woman in particular, I wouldn't want something glowing on my chest, drawing attention, in the same way I wouldn't want something super tight” (BM). These hot spots are not universal, and are influenced by factors such as body

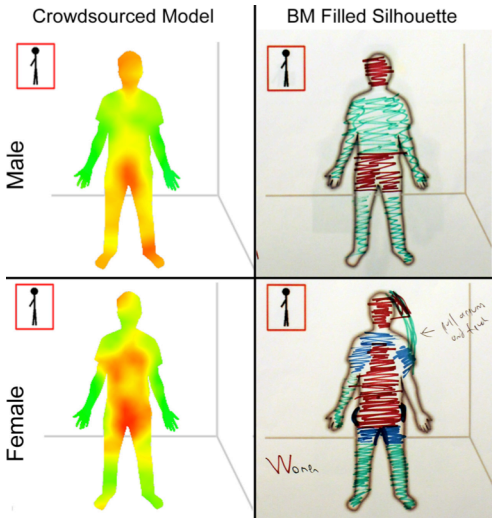

Figure 6. Comfort of touching interfaces appearing on ones’ own body, broken down by gender.

type: “For example, say if you were an apple shaped person, larger on the top. I wouldn't want anything clinging to me, touching me, lighting up here – stomach, torso, chest, and shoulder. If I were really pear.. like big around the hips, I wouldn't want anything lighting up around there” (BM).

Looking at gender-split heatmaps (Figure 6), this conservatism is reflected strongly, particularly with the upper torso and shoulder areas. These perceived gender complexities are nicely illustrated by a male/female pair of filled silhouettes (Figure 6, right) completed by BM, who has to accommodate body issues when assisting customers at her boutique. Unlike woman, “the chest region on a guy, and shoulder area, would be ok,” though the “hips, love handley area, is more sensitive “ (BM).

Of particular note, the hands and lower arms appear to sidestep these body image complexities, with both men and women. “Hands are universal - elbow down. Above elbow is difficult, more sensitive” (BM). “The [lower arm] is totally safe. Nobody ever says: ‘oh my, my forearms are so fat!’” (AD). This again is strongly reflected in the heatmaps.

Others Touching

The second half of the think-aloud exercise was concerned with how people would feel if another person asked to use an interface on their body. Questions surrounded what part of themselves would they “lend” first, and last, and why? This turned out to be an incredibly complex subject, fueled by opinions on e.g., personal boundaries, gender power imbalances, and physical anxieties [17,20,37].

Foremost, it is important to note that resistance to lending something to a stranger is not unique to the body or on-body interfaces. “I am so surprised by how people do not share cell phones. It is rude to ask someone at the airport, can I please use your cell phone? [A phone is] very personal” (YI). Giving someone a communications device is act of trust: “You can give them a pen, and you don't necessarily need it back. A phone, you definitely need back. Also [with a pen] they don't have access to your personal information, your contact information” (MT).

Overall, people seemed comfortable with close friends and family using an interface on their body. “If it were my friend, my hand would be ok, my arm would be ok” (CP) – matching how people would use their own bodies. However, reactions to unfamiliar people touching were much stronger. “Feels like loosing control.. vulnerable” (YI); “I would really hesitate” (JM); “It's an invasion into that persons space” (CP); “I would feel that my personal space would be invaded” (MT).

When dealing with strangers, two body locations were repeatedly suggested by our experts. Foremost was the arm, which is also popular for oneself. “The outside of the arm [is an] impersonal area” (JM); “It's not unusual for people to touch your arms” (TA); “Back of the forearms: combination of most practical to use and lease invasive.. It's not up here, close to where the breasts would be for a woman. Its not the hand, which that can feel really intimate - holding hands is a

particular type of touch" (MT). Other experts were more favorable to the hands: "Just my hand. It seems less personal. And I touch people everywhere. Back of hand is preferable, it seems less germy" (AD); "Only hands. That's what you'll give a stranger, you'll shake their hand" (TA); "Hands, it's where you are least vulnerable" (EC).

The other body area frequently suggested by our group of experts, which did not elicit much commentary prior, was the back and shoulder blade area. "I wouldn't mind lending my shoulder" (BM), "[it] feels.. really impersonal. [..] If I were going to tap that guy on the shoulder, that's where I can touch that person.. without making them mad" (JM). "It's almost like strangers can have here. It's like showing someone the cold shoulder.. It's protecting me more." (YI). "Just like you turn your back and someone with a paper writes on you. You don't do that on your front, or head, or somewhere else" (DI). From a touch sensitivity standpoint, "[its] pretty dead back there relatively speaking" (CP).

Regardless of preference for hand or back (which matches [20,37]), the other commonality was a desire not to have to face the person. "Back of shoulder, because they are not interacting with me, they are interacting with my surface. Having someone facing me and interacting with something on me is too social" (DI). "For a stranger: shoulder first… don't want them facing me" (YI). "[It's like being] face to face in an elevator, it's uncomfortable" (EC). "Front is a little more personal. Back is less personal" (CP). "[back] might be better than the forearm for strangers because you don't have to look at them" (MT). Similar comments were echoed about being constrained. "I'm happy to give my body as a display for communication, but I don't want to be constrained in my movement" (YI). "A strange man grabbing your arm or wrist is a very threading gesture. Someone touching your back over your clothes ... doesn't have the cultural association of power and threatening" (MT).

Others touching the legs for interactive purposes was generally viewed as impractical. When standing, "everywhere on the legs other than the upper thighs are awkward [for others to reach]" (MT). However, people were not keen on lending their thighs: "Wouldn't let them feel any higher than my knee" (BM); "The thighs are an awkward place to touch someone" (MT). Both YI and DI mentioned rules of thumb in their respective fields, as they often have to touch students as part of their instruction. These reinforce the primacy of the hand of shoulder as acceptable areas of touch between less familiar people. "Where is it boney, it's ok. But, where it is soft, that wouldn't be really good [for touching]" (YI). "This is a well established concept in social dance. There are five connection points that are acceptable: Shoulder, elbow, hands, hips and knees" (DI).

Symmetry

Two experts noted the importance of "symmetrical activities" (CP). "You wouldn't want to make any tool that makes the body sided" (YI). "Asymmetrical sends me business, either long time or repeated" (CP). For this reason, CP suggested the hands raised in front of you is "a natural place … you don't have to turn your neck," whereas turning the head towards either side is "uncomfortable for neck" (YI).

Thoughts on Acceptability of On-Body Interfaces

Several experts mused on the acceptability of such on-body projected interfaces if there were to be introduced. It was generally accepted the barriers surrounding touching oneself would begin to loosen if such technologies went mainstream. "I guest it depends on how commonplace this stuff becomes. If everyone is doing it then you aren't going to feel odd. If you're the first guy, you're probably not going to want to start with the inner thighs" (TA). "If this becomes significant for writing emails, touching even in the inside [of the groin] would become fine" (YI). Experts also made allusions to the apprehension surrounding the transition to mobile phones. "It's like when you got rid of your land line, and everyone just went all cellphone, there was a little while there me and other people my age where like, what if something goes wrong, you should have this backup landline. Which, of course, it didn't matter it turns out" (TA).

With respect to learning how to use an on-body system for the first time, DI put it eloquently: "When you start dancing with a partner you've never danced with before, you don't bust out the crazy moves right away, you start with the simple stuff and see how they react. You sort of build up a familiarity of the technical capabilities of your partner to find a good match. I feel that with a projection system like that, there is definitely going to be the first song, the first pancake - it's going to be kind of awkward."

OPEN DATA

For those wishing to do further analysis, we have made a copy of our 36,216 data points available online – please contact the authors for the latest URL. Our work could be extended in many ways, for example, by statistically comparing different regions of the body along dimensions such as appropriateness and gender.

CONCLUSION

A key finding is that few places on the body are reliably visually accessible and have universal appeal. The hands and arms have been a logical focus of previous research efforts – our results now quantitatively and qualitatively support this placement. In particular, the high mobility of the arms means they can be accessed on-demand, in a wide variety of poses. They also do not exhibit several key gender and interpersonal issues that limit the broad appeal of other body locations. Additionally, the arms are dexterous, are already our chief appendages for manipulating the world, and can assume contextually appropriate poses.

More specifically, the ideal area on the arm extends from just above the elbow, down to the hand. Above elbow locations suffer from reduced visual accessibility and also negative feedback as an area that was often sensitive for female users – both with respect to physical touch, but also possibly in drawing unwanted attention to this location. The hand was also highly rated, but our experts noted the flat and contiguous inner forearm was superior for interactive use. The fingers were seen as impractical for projected interfaces.

With respect to interpersonal touching – especially people you are less close with – it was noted that the side of the arm was the most acceptable location to touch. Of note, the shoulders also ranked highly. Regardless, the overall reaction was that of considerable hesitation about other people using one's body for interactive purposes.

A surprising new opportunity was the thighs – yet to be explored in any on-body system to date. The surface area can be large, has appeal across gender lines, and is immediately accessible by the hands – but only when in a seated pose, limiting its "on-the-go" ability. Due to both social and musculoskeletal constraints, the lower half (towards the knee) was viewed as ideal. However, the knees themselves are not highly rated due to increased nociception sensitivity and a notably irregular surface.

Finally, for some, on-body projected interfaces may seem like an uncomfortable direction to take computing. However, we believe that on-body interfaces can feel natural and intuitive if the design is informed. There is nothing particularly natural about grasping a small rectangular device in one's hand and poking fingers at it – yet, good design has made interacting with mobile devices second nature.

ACKNOWLEDGEMENTS

We thank Peter Kinnaird for helping to run the online study.

REFERENCES

1. Barnett, A. The dancing body as a screen: Synchronizing projected motion graphics onto the human form in contemporary dance. *Comput. Entert*., 7, 1 (2009), 1-32.
2. Cho, C. and Yang, H. Body-Based Interfaces. In *Proc. ICMI '02*. 466-472.
3. Coyle, D., Moore, J., Kristensson, P., Fletcher, P., and Blackwell, A. I did that! Measuring users' experience of agency in their own actions. In *Proc. CHI '12*. 2025-2034.
4. Deyle, T., Palinko, S., Poole, E.S., and Starner, T. Hambone: A Bio-Acoustic Gesture Interface. In *Proc. ISWC '07*. 1-8.
5. Faste, R. The Role of Aesthetics in Engineering. *Japan Society of Mechanical Engineers (JSME) Journal*. 28 (1995). p. 385.
6. Field, T. (2001) Touch. MIT Press, Cambridge, MA.
7. Gallace, A. and Spence, C. (2010). The science of interpersonal touch: An overview. *Neurosci. & Biobehav. Rev*., 34, 246-259.
8. Gallagher, S. (2005). *How the body shapes the mind*. Clarendon Press, Oxford.
9. Gavaghan, K.A., Peterhans, M., Oliveira-Santos, T. and Weber, S. A Portable Image Overlay Projection Device for Computer-Aided Open Liver Surgery. *IEEE Trans. on Biomedical Engineering*, 58, 6 (June 2011), 1855-1864.
10. Gustafson, S., Holz, C., and Baudisch, P. Imaginary phone: learning imaginary interfaces by transferring spatial memory from a familiar device. In *Proc. UIST '11*. 283-292.
11. Harrison, C., Benko, H., and Wilson, A. OmniTouch: wearable multitouch interaction everywhere. In *Proc. UIST '11*. 441-450.
12. Harrison, C., Lim, B.Y., Shick, A., and Hudson, S.E. Where to Locate Wearable Displays? Reaction Time Performance of Visual Alerts from Tip to Toe. In *Proc. CHI '09*. 941-944.
13. Harrison, C., Ramamurthy, S. and Hudson, S.E. On-Body Interaction: Armed and Dangerous. In *Proc. TEI '12*. 69-76.
14. Harrison, C., Tan, D., and Morris, D. Skinput: appropriating the body as an input surface. In *Proc. CHI '10*. 453-462
15. Hertenstein, M. J. (2002). Touch: Its communicative functions in infancy. Human Development, 45, 70-94.
16. Hertenstein, M. J. and Keltner, D. (2006). Touch Communicates Distinct Emotions, *Emotion*, 6(3), 528-533.
17. Hobye, M. and Löwgren, J. Touching a Stranger: Designing for Engaging Experience in Embodied Interaction. *International Journal of Design*, 5, 3 (2011), 31-48.
18. Holder, M. K. (1997). "Why are more people right-handed?" Sciam.com. *Scientific American*. Retrieved 2012-9-14.
19. Hornecker, E. and Burr, J. Getting a Grip on Tangible Interaction: A Framework on Physical Space and Social Interaction, In *Proc. CHI '06*. 437-446
20. Jones, S., and Yarbrough, A. E. (1985). A Naturalistic Study of the Meanings of Touch. *Comm. Monographs*, 52(1), 19-56.
21. Knapp, M. L. and Hall, J. A. (2006). *Nonverbal Communication in Human Interaction* (7th ed.), Wadsworth Publishing.
22. Löwgren J. Towards an Articulation of Interaction Aesthetics. *The New Rev. of Hypermedia and Multi.* 15, 2 (2009). 129-146.
23. Lyons, K., Starner, T., Plaisted, D., Fusia, J., Lyons, A., Drew, A., and Looney, E. W. Twiddler typing: one-handed chording text entry for mobile phones. In *Proc. CHI '04*. 671-678.
24. Mann, S. Smart Clothing: The Wearable Computer and WearCam. *Personal Technologies*, 1, 1 (1997), 21-27.
25. Manning, E. (2006). *Politics of Touch: Sense, Movement, Sovereignty*. Univ Of Minnesota Press.
26. Matthews, C., et al. Amount of Time Spent in Sedentary Behaviors in the United States, 2003–2004. *American Journal of Epidemiology*, 167(7), 875-881
27. Milgram, P., and Kishino, F. A Taxonomy of Mixed Reality Visual Displays. *IEICE Transactions on Information Systems*, vol. E77-D, no. 12 (1994).
28. Mistry, P., Maes, P., and Chang, L. WUW - wear Ur world: a wearable gestural interface. In *CHI '09 Ext. Abst*. 4111-4116.
29. Montagu, A. (1986). *Touching: the human significance of the skin* (3rd ed.). Harper and Row.
30. Noë, A. (2005) *Action in Perception.* MIT Press.
31. Post, E.R. and Orth, M. Smart Fabric, or "Wearable Clothing." In *Proc. ISWC '97*. 167-168.
32. Ross, J., Irani, L., Silberman, M., Zaldivar, A., and Tomlinson, B. Who are the crowdworkers?: Shifting demographics in mechanical turk. In *CHI EA '10*. 2863-2872.
33. Saponas, T.S., Tan, D.S., Morris, D., Balakrishnan, R., Turner, J., and Landay, J.A. Enabling always-available input with muscle-computer interfaces. In *Proc. UIST '09*. 167-176.
34. Sturman, D.J. and Zeltzer, D. A Survey of Glove-based Input. *IEEE Comp. Graph. and Appl.*, 14, 1 (1994). 30-39.
35. Thayer, S. (1982). Social Touching. In *Tactile perception: a sourcebook*. Cambridge University Press.
36. Thomas, B., Grimmer, K., Zucco, J., and Milanese, S. Where Does the Mouse Go? An Investigation into the Placement of a Body-Attached TouchPad Mouse for Wearable Computers. *Personal Ubiquitous Comput.* 6, 2 (January 2002), 97-112.
37. Tomita, M. (2008). An Exploratory Study of Touch Zones in College Students on Two Campuses. *Californian Journal of Health Promotion*, 6(1), 1-22
38. Valela, F., Thompson, E. and Rosch, E. (1991). *The Embodied Mind: Cognitive Science and Human Experience*. MIT Press.
39. Weigel, M., Mehta, V., Steimle, J. More Than Touch: Understanding How People Use Skin as an Input Surface for Mobile Computing In *Proc. CHI '14*.
40. Wilson, F. (1998). *The Hand: How its use shapes the brain, language, and human culture*. Pantheon.
41. Yamamoto, G. and Sato, K. PALMbit:A Body Interface utilizing Light Projection onto Palms. *Jour. of The Inst. of Image Information and Television Engineers*, 61, 6 (2007), 797-804.