Body-based user interfaces[1]

Paul Strohmeier, Aske Mottelson, Henning Pohl, Jess McIntosh, Jarrod Knibbe, Joanna Bergström, Yvonne Jansen and Kasper Hornbæk

Abstract

The relation between the body and computer interfaces has undergone several shifts since the advent of computing. In early models of interaction, the body was treated as a periphery to the mind, much like a keyboard is peripheral to a computer. The goal of the interface designers was to optimize the information flow between the brain and the computer, using these imperfect peripheral devices. Toward the end of the previous century the social body, as well as the material body and its physical manipulation skills started receiving increased consideration from interaction designers. The goal of the interface designer shifted, requiring the designer to understand the role of the body in a given context, and adapting the interface to respect the social context and to make use of the tacit knowledge that the body has of how the physical world functions. Currently, we are witnessing another shift in the role of the body. It is no longer merely something that requires consideration for interface design. Instead, advances in technology and our understanding of interaction allows the body to become part of the interface. We call these body-based user interfaces. We identify four ways in which the body becomes part of the interface: (1) The interaction might occur on or in the human body, for example using implanted tactile stimulation or touch interfaces on the body. Here the material of the body becomes part of the interface. (2) The interaction changes the morphology of the body and corresponding control structures, for example by providing users with additional skills, such as drawing or playing instruments or additional limbs that help complete complex tasks. Here the shape of the body, or the corresponding ability to act, is affected by the interface. (3) The interaction engages with or modifies how we perceive the world, for example by manipulating the sense of direction in VR or allowing users to experience non-existent stimuli, such as mid-air friction. Here, the idiosyncrasies of multi-modal perception and perceptive acts become part of the user interface. Finally, (4) the interaction might engage with the experience of having a body, for example by manipulating the sense of body ownership, location, or agency. Here the introspective access to one's own body is used in the design of the interface. In this chapter, we present a brief history of the body's role in human–computer interaction, leading up to a definition of body-based user interfaces. We follow this by presenting examples of interfaces that reflect the different ways in which interfaces can be body-based. We conclude by presenting outlooks on benefits, drawbacks, and possible futures of body-based user interfaces.

---

[1] This is an author copy of a book chapter published as part of The Routledge Handbook of Bodily Awareness; Edited By Adrian J.T. Alsmith, Matthew R. Longo. DOI https://doi.org/10.4324/9780429321542. Please note that content is laid out differently in this version and that page numbers do not correspond to the version of record included in the above cited handbook.

1 | Introduction

Historically, computing has not concerned itself with the bodies of its users. The first digital computers were designed to execute predefined programs without any user intervention. Once computing became interactive, input and output were handled through the keyboard, the monitor, and, later on, the mouse. Through those devices, the computer user's body was essentially reduced to a pair of eyes for observing the output and ten fingers for pressing buttons and moving a mouse around. As complex and wondrous as the human body is, the computer could receive input only from the tips of its fingers. If the rest of the human body was considered at all, this happened primarily in the context of ergonomics and task performance. Accordingly, the models popular for describing interaction, such as Fitts's law, Miller's law, and Hick's law, focused on information transfer. The body was reduced to a limiting factor, a constant, providing an upper bound to the achievable throughput.

This view is reflected in Card, Moran, and Newell (1983)'s notion of the model human processor, which describes users in terms of their information processing and storing ability. Beyond that, Card et al. did not consider how the bodies of computer users matter. Other classic theorists of computing also focused mainly on higher level cognitive abilities. For instance, Licklider's idea of human–computer symbiosis (1960) and Engelbart's idea of augmenting human intellect (1962) were concerned with intellectual, non-bodily skills.

Since then, the field of human–computer interaction (HCI) has evolved its view of users and their interactions with computers. Instead of seeing the users and their bodies only as information processors that can press buttons, the field has come to include social and contextual perspectives.

One such perspective is that of situated interaction, inspired by the fact that the social, organizational, and personal contexts in which users are situated influence their interactions with computers. As users' bodies shape these contexts and situations, the body plays a central role in how one interacts with computers (Suchman, 1987). Another perspective is embodied interaction, which emphasizes that when humans interact with computers, we do so not as disembodied minds, but as thinking bodies that act in the world (Dourish, 2004). These new perspectives in HCI are complemented with work in cognitive psychology and design that discusses how users' bodies play a more central role in interaction; see, for instance, Klemmer, Hartmann and Takayama (2006) and Kirsh (2013).

As the views of users and their bodies have developed, new types of user interfaces (UIs) have incorporated them. UIs that involve the users' bodies better include tangible user interfaces (Fishkin, 2004). In contrast to graphical user interfaces, where one mainly manipulates virtual objects with the cursor, tangible user interfaces are physical objects that the user can directly interact with. In such UIs, the interface takes material form and becomes open to a richer set of touches, grasps, and manipulations. Another type of UI which uses the body are natural interfaces. These are designed to use more direct and intuitive interactions through modalities such as touch and gestures (Wigdor and Wixon, 2011). Using advances in sensing, these interfaces allow users to interact with computers by moving around, speaking, or changing their posture.

Considering the users' bodies in researching interaction has led to UIs that involve more and more of the body. We posit that the next step in this development is to design with bodies as a part of the UI, not merely a means of input to it. In such body-based user interfaces, input and output occur on and in bodies, and the separation between user and interface fades away.

Within the field of HCI, the development of body-based user interfaces has accelerated over the past 15 years, and we have seen technology blending with bodies in more direct ways than before. Examples of this blending include using body surfaces for touch input (Harrison, Tan and Morris, 2010), inducing itching electrically (Pohl and Hornbæk, 2018), using hardware to give a user extra limbs (Leigh and Maes, 2017), using perception to modify a user's actions (Razzaque, Kohn and Whitton, 2005), and changing the boundary of what a user perceives as their body (Slater et al., 2009).

Thinking about such user interfaces in a structured way is important for three reasons. First, body-based user interfaces showcase a future where human abilities, rather than technological opportunity, might drive technological development. Second, the thinking behind body-based user interfaces draws on psychology, cognitive sciences, philosophy, sociology, and many other disciplines represented in this handbook. These interfaces, therefore, illustrate applications of the dramatic changes in how various forms of scholarship view the body. Third, body-based user interfaces also contribute to research on bodies, including on how action and perception are intertwined, how interoception works, how agency may be affected, and many other topics.

When designing a UI for the body, one's implicit view of what a body is has a strong influence on the type of UI one creates. In this chapter, we structure our discussion of body-based user interfaces along four such views. This not only serves as a convenient structure for this chapter, it also helps organize, discuss, compare and contrast different ways in which interfaces are body-based. The views which we use to structure our discussion are a material, a morphological, a sensorimotor, and an experiential view of the body. For each view, we discuss the associated opportunities and provide examples of corresponding UIs. We also outline some open challenges and next steps in realizing body-based UIs.

2 | What are body-based user interfaces?

The user interface to an interactive computer system comprises all those parts of computing that users encounter as they use the systems. This includes input devices, such as a touchpad or a mouse, and output devices, such as a virtual reality headset or a smartphone display. The user interface also concerns how inputs, such as mouse movement and key presses, are processed, how they control the mouse cursor's behavior or other representation in the user interface, and, ultimately, how they affect data in the back-end of the interactive system. The way the user perceives and understands output is another key consideration for a designer who aims to tap relevant sensory modalities in a manner that makes interaction proceed smoothly.

The types of traditional user interfaces are well known and include the mouse, displays, widgets, dialog boxes, and much more. We understand their input mappings and control (Zhai, 1998), create taxonomies of ways we interact with them (Buxton, 1994), and systematic descriptions of their design space (Card, Mackinlay and Robertson, 1990). Such framing is missing for these newer, body-based user interfaces: how does an on-skin display relate to a device that uses electrical signals to move the user's limbs?

Many early approaches conceptualize or design user interfaces that engage with our bodies, instead of focusing on screens and desktops. These approaches include "body-based interaction" (Waller, Loomis and Haun, 2004; Milne, Antle and Riecke, 2011) for systems whose users rely on vestibular or proprioceptive information, "full-body interaction" for systems that track the entire body (Maes et al., 1997), "body-centric interaction" for systems where natural gestures are performed in spaces relative to the body (Shoemaker et al., 2010), "inbodied interaction" where systems draw on the body's internal, physiological processes (schraefel, 2020), "body-machine interface" in which robotic devices are controlled by physiological signals or movements (Casadio, Ranganathan and Mussa-Ivaldi, 2012), and "human–computer integration" (F.F. Mueller et al., 2020a) which refers to a broader area not only including UIs which use the body, but also encompassing human-in-the loop AI or integration between groups of people and devices.

We integrate and structure these approaches within the term body-based user interfaces. We use this term for two reasons. First, the notion of being "body-based" stresses that the concept builds upon the foundation of the body. In the complex relationship between technology and body, the latter is in focus, while the former is near, on, or in it. In that way, the body, including how it shapes our access to the world and how we experience it, is given a special mediating role in our use of the interactive system or computational resources. Following the definition of user interface, this mediating role may take a variety of forms. For instance, bodies may give input to an interactive computer system, or bodies may serve as the substrate for output by being projected on or electrically actuated.

Second, the phrase "user interfaces" emphasizes that a body-based user interface is a concrete technology. This distinguishes body-based user interfaces from devices resulting from body-centric design practices (Loke and Robertson, 2011; Höök et al., 2017). This focus on the technology might appear odd, as superficially, it seems that all user interfaces are body-based. After all, users control all interfaces with their bodies. Users are constantly interacting in some pose, with some sense of balance, and with some experience of their body. Users might speak a command, touch the screen of a phone with a finger, or move a mouse with a hand. However, the user interface basically ignores the body. For example, when one moves a cursor to a specific location, the only relevant thing is that the mouse is moved. It doesn't matter if one accomplishes this movement using a hand, one's nose, or a pair of chopsticks: as long as the required movement of the mouse is performed, the result will be the same. In contrast, in some newer user interfaces, bodies are central, whether because the interface interacts with the user's sense of balance (Byrne, Marshall and Mueller, 2016) or experience of their body (Tajadura-Jiménez et al., 2015), or because the interaction uses the body as a medium (Harrison, Tan and Morris, 2010).

To understand body-based user interfaces better, it is useful to compare them to other concepts. For example, body-based user interfaces share many similarities with wearable computing. However, there are clear distinctions. Consider iSkin (Weigel et al., 2015) – a thin, stretchable sensor that can be placed on the body like a temporary tattoo – and zPatch – a similarly thin pressure sensor designed for integration with clothing (Strohmeier et al., 2018). iSkin was explicitly designed to be placed on the body. Thus, interacting with iSkin provides the user with an experience of interacting with their body, making it body-based. A jacket with zPatches might be worn, or it might be hanging over a chair. In both cases, the user can interact using zPatch. The placement on the body is incidental, so this interface is not body-based. In general, wearable computing shares an interest with body-based UIs in the miniaturization of devices, and body compatibility, and the potential for use in a wide range of activities (Knibbe et al., 2021). However, many wearable devices are not body-centric, and a body-based user interface is not necessarily wearable.

Body-based user interfaces also share much common ground with assistive technologies, such as prostheses and implantable cardiac monitoring systems. These technologies have been extensively discussed in the literature, both with respect to their engineering and their psychological implications. Typically, they are intended to recede from attention. In most cases, they only alter the user's experience or draw attention to themselves when they fail. Body-based user interfaces, by contrast, are designed to provide interactive experiences.

Body-based interfaces are not bound to any particular technology. For example, a number of body-based user interfaces use VR, as VR can provide rich sensory stimulation across multiple senses coupled with high resolution tracking for rich gestural input. Users' bodies and movements in VR environments can be captured in close visuomotor synchrony, nearly convincing subjects that their virtual body is, in fact, their own body (Kilteni et al., 2015). As virtual bodies are easier to manipulate than physical bodies, VR provides a powerful platform for implementing body-based interfaces. At the same time, many VR environments consist merely of passive content which the user interacts with through clicks on a controller, much as they would interact with a traditional UI. So while many body-based user interfaces use VR, not all of them do, and most VR interfaces are not body-based.

In sum, an emerging class of user interfaces engages with the body in new ways. These user interfaces are of interest to computer science and many other areas of scholarship. Next, we discuss four views of the body which lead to different types of body-based user interfaces.

3 | Views of body-based user interfaces

Body-based user interfaces are typically created with particular implicit views of the body. Those views shape what the interface aims to do, which literature and knowledge about the body it draws on, and what technologies it uses. Thus, organizing this chapter around these views provides a framework and a vocabulary for discussing some of the technical and scientific ambitions of body-based user interfaces. Our scope is intentionally broad, and is intended to foster discussion on how bodies are used in HCI, rather than demarcating a specific area of research. We focus on four areas of research inspired by four views of the body:

1. The **material body**. The interaction might occur on or in human bodies, for example using implanted tactile stimulation or touch interfaces on the body. Here the material of the body becomes part of the interface.

2. The **morphological body**. The interaction changes the morphology of the body or the corresponding control structures, for example by providing users with additional limbs or with additional skills such as drawing or playing instruments. The interface affects the shape of the body or its ability to act.

3. The **sensorimotor body**. The interaction modifies how users perceive the world, for example by manipulating the sense of direction in VR or allowing users to experience non-existent stimuli such as mid-air friction. Here, the idiosyncrasies of multi-modal perception and perceptive acts form part of the user interface.

4. The **experiential body**. The interaction engages with the experience of having a body, for example by altering the sense of body ownership or agency. Here the experience of one's own body becomes part of the interface.

These views amount to a four-part definition. If a UI fits one or more of them, we consider it a body-based user interface.

Articulating these views serves three purposes. First, we provide a clear definition of body-based user interfaces, something missing from earlier work. Shoemaker et al. (2010) presented four design principles and Klemmer et al. (2006) presented five design themes. Neither paper, however, articulates a clear definition of what the design principles or themes are intended to achieve.

Second, articulating these views helps create research agendas and identify gaps in theory and practice that are worth exploring.

Third, our definition provides a framing for further discussion within and across the different views. We believe that to ground the discourse surrounding the role of the body in HCI, body-based UIs need to be discussed through the examples of concrete technologies, with a focus on the experiences of the humans using them. By articulating the four views, and structuring our discussion of resulting research directions accordingly, we show how even if two pieces of work in this area might appear radically different from one another, they might have a shared appreciation of the central role of the body, but different views of what a body actually is.

Figure 1: Left: Body-based user interfaces that use the material of the body for input and output on the skin (Weigel et al 2017). Middle: Implanted devices are always present and inconspicuous (Strohmeier and McIntosh, 2020). Right: Using itching for notifications (Pohl and Hornbæk, 2018).

Next, we discuss research inspired by each view, the potential applications that might develop from it, and preliminary work in that area.

3.1 The material body

Pragmatically, the body can be viewed as a physical thing, much like a book or a jacket. In the same way as one might augment a book or a jacket with electronics to make them interactive, the body can be augmented. This view inspires research into how technologies can be attached to or embedded within bodies and how to ensure that those technologies are compatible with the body. With these things in mind, a user interface is body-based if input or output happens on or in the body. Rather than keys for input and a screen for output, these interfaces use muscles, tendons, and, especially, skin.

Consider a few representative user interfaces. Figure 1, left, shows work by Harrison, Tan and Morris (2010). This interface allows people to provide input directly on their skin. This is achieved by processing signals from microphones placed on the arm; these signals can pinpoint the location of touch with remarkable precision. In that way, the forearm can be repurposed as an input surface. Figure 1, middle, shows an implanted magnet (Strohmeier and McIntosh, 2020) for tactile interactions. Pioneering work by Holz et al. (2012) on implantable devices explored how implantable devices might sense input and provide a visual display through the skin. Figure 1, right, shows a wristwatch-like device designed by Pohl and Hornbæk (2018) that electrically induces the sensation of itching to deliver notifications.

These examples highlight reasons to use the material of the body for user interfaces: the skin's availability, versatility, and size; the convenience of user interfaces on or in the body; and the ability to use the body's natural features and processes. Next, we discuss each of these reasons in turn.

3.1.1 Constant availability of the skin

The skin is the material of the body that has been used most extensively for body-based user interfaces. It is large (about 2m^2), sensitive, and always with us (Steimle, 2016). For input, most work has focused on the technical challenges of making touch input work. Wearable cameras have been used for providing input on the forearm. The camera is placed on the shoulder so that the forearm and the opposing hand are in view, enabling users to perform taps and swipes on the skin (Harrison, Benko and Wilson, 2011). Camera-based tracking is often combined with the projection of menus, GUI elements, and other output on the skin (e.g., Harrison, Tan and Morris, 2010; Harrison, Benko and Wilson, 2011; Wang et al., 2015). Another method for tracking touches on the skin is acoustic sensing. Skinput (Harrison, Tan and Morris, 2010), see Figure 1, uses bioacoustic sensing to distinguish touches at different, pre-determined locations on the hand. When the hand is tapped, the impact of the tap is captured by an array of microphones on the forearm. This acoustic information can be used to correctly identify where the hand was tapped.

One of the most exciting advances in on-skin UIs is the interactive temporary tattoo. SkinMarks (Weigel et al., 2017) are thin, conforming, conductive, electroluminescent temporary tattoos that track touch and deformations of the skin, provide visual output, and are haptically transparent – in other words, the user cannot feel they are there. Interactive temporary tattoos have also been used to provide haptic feedback on the body. Tiny electrodes can provide electrical stimulation to mechanoreceptors. This makes it possible to electrically induce tactile experiences (Withana, Groeger and Steimle, 2018). The skin can also be deformed as input. As pointed out by Bergström, Mottelson and Knibbe (2019), skin can be pressed, pushed, or pinched. Deformation input can be used to select a point or a magnitude on a slider, to express emotions, or to control a 3D model with one finger. All these things can be sensed and can serve as expressive input.

3.1.2 Convenience of the body

Directly integrated user interfaces on or in the body can be more convenient than ordinary devices. Body-based user interfaces are always with us, comfortable to use, and seamlessly compatible with our daily lives. In their seminal paper on epidermal electronics, Kim et al. (2011) argued that epidermal devices will be able to provide "long-lived, robust electrical contacts that do not irritate the skin … with overall sizes, weights, and shapes that do not cause discomfort during prolonged use." Heffernan, Vetere and Chang (2016) described how users often find traditional biometric devices uncomfortable to wear during exercise, or unable to sustain environmental conditions as well as the body. Implanted devices offer one potential solution, offering rich input and output opportunities (Holz et al., 2012; Strohmeier and McIntosh, 2020) while leaving the user unencumbered during intense activities. Such devices are fast becoming a reality, as miniaturization has led to smaller and lighter-weight technologies.

The simplest interactive implant is a magnet, which can provide surprisingly high utility. Magnets provide a tactile experience of varying electromagnetic fields (Heffernan, Vetere and Chang, 2016). The experience of these vibrations has been explored by Strohmeier and McIntosh (2020) and Harrison, Warwick and Ruiz (2018); findings from both studies suggest that the bandwidth of perceptible vibration may be broader inside the skin than outside it. Strohmeier and McIntosh (2020) and McIntosh et al. (2019) also suggest methods by which an implanted magnet can be controlled by an external device and how an external device can be controlled by the magnet.

Beyond simple, passive magnets, implantable devices will be able to sense a range of signals currently unavailable for use in user interfaces, such as temperature of the gut (Li et al., 2019). Most research on implantable devices, however, is done for medical purposes and not for interaction (Vasisht and Zhang, 2019).

3.1.3 Using the natural features of the body

A further way of using the material body in user interfaces is to use the unique material features and processes of the body.

The skin and the body can be used as landmarks for interaction. Landmarks, such as bones and features of the skin, can provide visual cues for input targets, or haptic cues for touching that support spatial memory about locations on the body. For example, a mobile phone's menu can be mapped onto the hand of the user (Gustafson, Holz and Baudisch, 2011), such that the user learns how different knuckles might link to different apps, or how different parts of the palm link to different numbers on the dial pad. Users' spatial memory has been shown to benefit from a wide variety of on-body landmarks (Wagner et al., 2013), such as freckles, phalanges of fingers, metacarpal bones on the hand, and scars and veins visible on the skin (Bergström-Lehtovirta, Boring and Hornbæk, 2017). The landmarks act as memory aids because people may link them to previous life experiences (e.g., scars to events), metaphors (e.g., veins to scenery), and orders (e.g., family members on the five knuckles). At the same time, such landmarks can provide haptic guidance for on-skin input (Weigel et al., 2017).

Using natural features of the body is not a new idea, but builds upon old traditions of makeup and body art. Within HCI, various approaches blend the aesthetics of makeup and body art with technology (Vega and Fuks, 2014; Kao, 2017). Methods used for applying makeup and body art might also be used as design tools for epidermal devices (Pourjafarian et al., 2021).

Our bodies are not inert, but undergo constant changes, fast and slow, great and small. They cough, they giggle, they secrete odors, they excrete solids and fluids; they may ejaculate; they may menstruate (Campo Woytuk et al., 2020). Some of these processes have been used for interaction with computers. For example, ingestion and digestion have been explored by a swallowable game system (Li et al., 2019) The players each swallow a pill that measures the temperature of their interior. The game then gives them a target temperature, and the players consume hot or cold substances such as tea or ice cream, competing to reach the target temperature fastest. The act of urination has been repurposed as an input method for games (Maynes-Aminzade and Raffle, 2003). Often, bodily functions are closely linked – such as ingestion, digestion, and excretion – and designing for one might open up a larger design space with others. A similar linking of functions might be itching and scratching, which Pohl and Hornbæk (2018) have explored for creating a personal, private, nearly subconscious means of interaction.

A part of our lives that is technologically mediated is fertility and reproduction. However, this topic has barely emerged in HCI, and few interactive systems deal with fertility and reproduction. Notable exceptions include systems for fertility tracking that can be shared between partners (Flemings et al., 2018; Homewood, Bewley and Boer, 2019). These systems, however, do not actively interact with the body.

3.2 The morphological body

The body can also be viewed as something primarily defined by its structure. The body's structure shapes what we can do: two legs allow us to walk upright, opposing thumbs help manipulate objects, and so on. In addition to the physical structure of the body, the body also has a control structure: some movements might be initiated by the motor cortex, while simple behaviors might be initiated in the spine. Digital technologies can become part of these control structures, as when an autonomous prosthetic hand grasps an object. When we speak of these phenomena, we refer to the morphological body (Leigh, 2018). Interfaces that are concerned with the morphological body manipulate some aspect of the body's shape, the arrangement and degrees of freedom of its limbs, the number of limbs, or how limbs are controlled. Such bodily adaptations allow us to overcome some of the limitations of physical bodies and enable new ways of expression and engagement with the world.

For example, one might augment the ability of the body to perform specific tasks. McIntosh et al. (2020) demonstrated a computational approach to such optimization as they iteratively adjusted a user's avatar in a VR environment, lengthening its fingers, hands, and arms, to improve the user's physical performance in various targeting tasks (Figure 2, left). Alternatively, instead of changing the body, one can change its control structure, for example interweaving computer and human control by means of electrical muscle stimulation (EMS). In this condition, the human and the computer share control.

Lopes, Jonell and Baudisch (2015) demonstrated an EMS system that communicates how tools are used by making the user perform the corresponding actions (Figure 2, middle). Finally, changes to the morphology might be used for personal or artistic expression. Hattwick et al. presented a prosthetic spine that acts as a music controller (2014). While the dancer's range of motion is slightly constrained, her expressive abilities are extended through sound manipulation resulting from movement of the additional spine (Figure 2, right).

In sum, the goals of morphological UIs include skill augmentation, interwoven computer and human control, as well as personal and artistic expression. These goals are typically achieved by means of wearable robotic systems, avatars in VR, or electrical muscle stimulation (EMS).

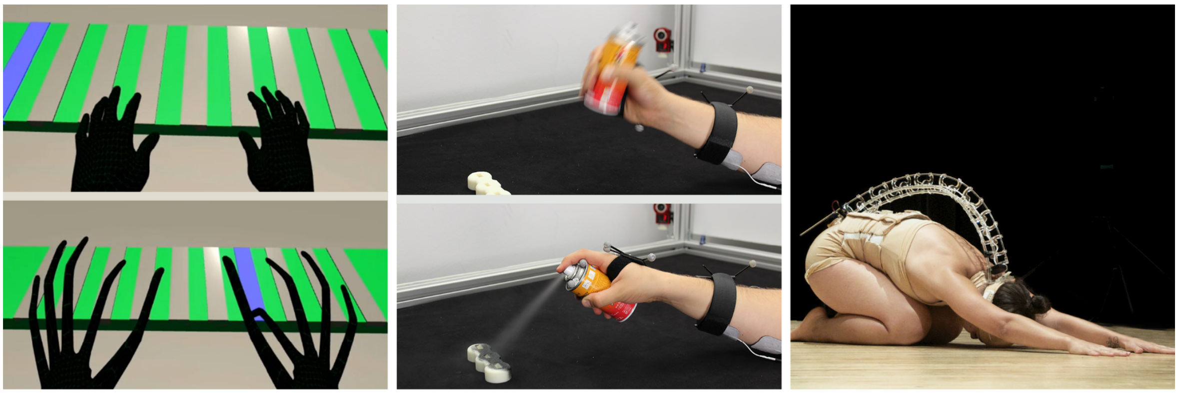

Figure 2: *Left*: Iterative optimization for completing a targeting task distorts the shape of the user's hand. Users controlling a reshaped avatar (bottom) are more efficient at performing a task (McIntosh et al., 2020). *Middle*: Objects convey how they should be used. When the user lifts the tool, a digital system controls the user's arms, showing how to use the tool (Lopes et al., 2015). *Right*: A dancer with a prosthetic instrument in the form of an external spine. This prop constrains her movements, requiring her to rethink how she moves, but also sonifies her movements: that is, in flexing it and twisting it, she makes synthesized sounds (Hattwick, Malloch and Wanderley, 2014).

3.2.1 Augmenting abilities

Many of the technologies used for morphological interfaces have their roots in assistive technologies. Early technologies using electrical muscle stimulation (EMS) include systems that allow paraplegic people to ride a bicycle, propelled by their legs (Kirkham et al., 2002). EMS need not be used only on limbs. It has also found use in restoring bladder control for paraplegic patients (Perkins et al., 2002). Of course, movement can also be restored in less invasive ways, for example by using an exoskeleton (Pons, 2010). Especially with exoskeletons, the border between restoring ordinary function and surpassing ordinary function can sometimes become blurry (Matthew et al., 2015).

Within the wider HCI community, such blurriness has been embraced, for example within the concept of assistive augmentation (Huber et al., 2018), which often provides users with tools that not only restore function, but provide the user with additional abilities that a non-assisted person does not have. Similarly, the Cybathlon, an international competition that took place in 2016 and 2020 as a challenge for engineers and differently abled athletes, rewards engineering that not only provides restoration of function, but also pushes the boundary toward superhuman ability (Riener, 2016).

The conceptually simplest robotic approach to augmentation might be an exoskeleton that provides users with artificial strength (Thomas, Coholich and Sentis, 2019) or supports the execution of tasks by recording movements and playing them back on command (Goto et al., 2018). A stranger case is that of robotic systems that provide extranumerary limbs, as they enable qualitatively new ways of doing things. These include new ways of grasping objects provided through supernumerary fingers (Leigh and Maes, 2016) and improved multi-tasking supported by extra limbs (Saraiji et al., 2018).

An alternative to robotic systems is EMS, which has the benefit over robotic approaches that it is comparatively lightweight. Instead of requiring motors or pneumatics, it relies on the actuation force of human muscles. An exciting concept is that of skill-sleeves (Knibbe et al., 2017), comfortably wearable high-density electrode arrays capable of reading muscle activity to infer body positions and to replay them using EMS (Knibbe et al., 2021). Once optimized, such sleeves might make it possible to record the movements of an expert piano player and replay them through a novice's body. Control strategies of such devices and user agency with respect to action initiation are among the most important open research questions for both robotic and EMS based systems (Leigh and Maes, 2018; Maekawa et al., 2020; Danry et al., 2021).

Finally, VR and virtual avatars are a powerful way of exploring human augmentation. While VR has the obvious limitation that it does not actually impact physical bodies, it is a powerful tool for exploring many open research questions around motor plasticity. Avatars might have extra arms (Won et al., 2015; Laha et al., 2016) or arms that reach far into space (Laha et al., 2016). Studies have shown that we are capable of adapting to bodies with morphologies different from our own. We gravitate toward using the limb most suited for a task. When we have the option to use a third arm, we can actually use it to complete targeting tasks more efficiently (Won et al., 2015). Building on this idea are explorations of dynamic bodies that adapt to tasks. Results demonstrate that users' efficiency in task completion can be improved with optimized bodies (see Figure 2, left).

3.2.2 Information and computer–human control

Morphological interfaces can also be used as an alternative channel to provide information to users. This is used by Lopes et al. for their concept of proprioceptive interaction. They use EMS to control the body pose of a user as a feedback channel. The user can provide input to the system using gestures while observing their own body to understand the computer output. Visualize it this way: there are electrodes on your arm. They can change the angle of your wrist. You can use the wrist angle to set some value, for example music volume. The computer can provide information to you, for example the percentage of a task you have completed, also by moving your wrist. (Lopes et al., 2015). Another system, Affordance++, communicates hints on how to use devices by using EMS. Affordance++ makes the user perform the motions that are required to use the device. (Lopes, Jonell and Baudisch, 2015). The opposite to artificially inducing movement would be to constrain movement. Pohl et al. deployed such a mechanism to help runners gauge their speed based on the available range of motion in their knees (Pohl, Hoheisel and Rohs, 2017). Similarly, motion constraints can be used to convey realism in VR. For example, a drop in temperature has been communicated using compression feedback, simulating the freezing of limbs (Al Maimani and Roudaut, 2017) and the presence of walls and electric shocks is simulated by constraining movement with EMS (Lopes et al., 2017).

Sometimes it is not necessary for the user to consciously be made aware of relevant information. Instead, the computer can directly cause appropriate actions without the user's conscious involvement. For example, when a user is walking toward an obstacle, the computer can adjust their path to steer clear of the object (Pfeiffer et al., 2015). Another system uses the users' hands to sketch models of wind tunnels using EMS. A user might want to know how a hand sketched car would behave in a wind tunnel. A computer can add this information to the sketch, by controlling the users' hands with EMS (Lopes et al., 2016). Finally, if target actions are known, computers can improve reaction time via EMS, allowing users to catch fast-moving objects or successfully take photographs of events that last for only fractions of seconds (Nishida and Suzuki, 2017; Kasahara, Nishida and Lopes, 2019). An interesting observation about many of these systems is that users often do not experience these actions as machine-initiated.

3.2.3 Artistic expression and alternative bodies

Morphological interfaces might also be used for personal expression. For example, Monarch, a robotic wearable device, consists of two physical, muscle-controlled wings mounted on top of the shoulders. Users can flex their biceps to wave with the wings, in a similar manner as one might wave at a friend. Monarch combines modifications to both internal and external morphology to create a physical extension of body language (Hartman et al., 2015). Similar motivations can be found behind various interactive wearable ears (Svanaes and Solheim, 2016) and tails (Svanaes and Solheim, 2016; Nabeshima, Saraiji and Minamizawa, 2019), though the latter can also be used for augmenting the human sense of balance.

The practice of body modification for self-expression far predates HCI. It has been speculated that the practice of body art is as old as human culture itself (Watts, 2009). In contemporary art, this practice itself has been augmented with technology – Stelarc is especially well known for pushing the boundaries of alternative and remixed bodies (Shanken, 2009; Stelarc, 2020). For Stelarc, the remixed body is the artistic performance itself; bodies that have been modified, extended, or constrained in some way can also be used as tools for performing art. Hattwick et al. used prosthetic instruments such as the spine mentioned above that allow dancers to create sounds (Hattwick, Malloch and Wanderley, 2014), while Reed and McPherson used bio-signals to augment vocal expression (Reed and McPherson, 2021).

3.3 The sensorimotor body

A third view sees the body as that which acts within and perceives the world. The body is framed as facilitating a loop of motor actions and corresponding sensory input that allow us to interact with the world. Work inspired by such a view might manipulate perception to change action, manipulate action to change perception, or use what we know about how action and perception interact to infer things about the user or their world. We can begin to explain these things by noting that people perceive relevant stimuli from the world and respond to them. Such a response, in turn, consists of effects on the world, which again influence the perceived stimuli. This way, perception and action co-constitute each other, and should be thought of as a unit or a sensorimotor loop (Uexkull, 1934). One might be tempted to disregard the idea of action co-constituting perception as mundane: of course we need to reach out and touch an object, if we wish to feel it. However, phenomena such as image fading during paralysis of the eye (Stevens et al., 1976) or optical illusions based on the Troxler effect in which unvarying stimuli disappear from our perception (Clarke, 1960) highlight how integral action is for perceiving the world.

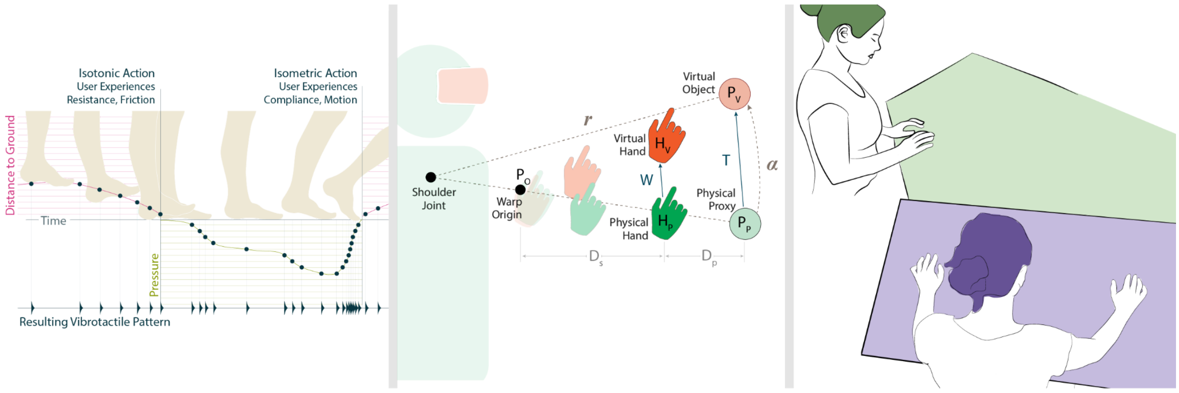

Figure 3: Left: Tactile impulses based on foot height (purple) and pressure (green) lead to perceptions of resistance and compliance, respectively (Strohmeier et al., 2020). Middle: A sketch showing haptic retargeting. The user reaches for the virtual object (Pv) but will touch the physical object (Pp). The trajectory of the virtual hand (Hv) and physical hand (Hp) are also indicated (Gonzalez and Follmer, 2019). Right: When one is manipulated by a virtual environment to assume an expansive pose, a so-called "power pose," one's behavior does not become more risky (Jansen and Hornbæk, 2018).

There are many ways in which sensorimotor processes can be used in body-based user interfaces. One might create artificial sensorimotor loops that enable perception of stimuli that are not actually present, for example, creating the sensation that hard surfaces give way somewhat when pressure is applied to them (Kildal, 2011; Strohmeier et al., 2020) (see also Figure 3, left). One might also use sensorimotor loops to subtly manipulate users' behavior by intentionally providing sensory information incongruent with their body's actual position. This approach can be employed for increasing tactile realism in VR (Azmandian et al., 2016; Gonzalez and Follmer, 2019) (Figure 3, middle). Leveraging the primacy of visual perception, one can also lead a person to walk in circles while believing that they are walking in a straight line (Razzaque, Kohn and Whitton, 2005). Finally, HCI researchers have also explored links between physical and mental states, using body poses to infer what moods people are in (Michalak et al., 2009), or even manipulating actions or poses to induce target mental states. Jansen and Hornbæk explored the question of whether body poses affect risk taking: they positioned test subjects in front of displays that led them to assume more or less expansive body positions, for example by simultaneously pushing two buttons set far apart or pushing two buttons set closer together; the study found no effects of pose on risk taking (Jansen and Hornbæk, 2018) (Figure 3, right).

Goals of sensorimotor body-based user interfaces include the creation of what might be called virtual perceptions. Ordinary perceptions result from an interplay of motor action and corresponding sensory stimuli. It is possible to create artificial action/sensory stimulus couplings by measuring the action and then counterfeiting a stimulus. This process can provide an alternative way of communicating information or immerse users in virtual worlds. Related systems might not aim to create perceptions, but rather use perception to subtly change behavior, including for immersion in VR. For example, it's possible to use perceptual tricks to make someone walk in circles while they believe they are walking in a straight line. They will feel like they are walking through an endless virtual space, when in reality they are just circling and circling (Razzaque, Kohn and Whitton, 2005). Finally, an open question is whether such systems can manipulate user behavior beyond simple movements, including manipulating mood or even higher level concepts such as creativity or risk taking.

3.3.1 Enabling perception of virtual stimuli

Body-based user interfaces may enable users to perceive non-existent stimuli: for example, sensations of softness and flexibility when one is standing on a hard surface (Strohmeier et al., 2020) or the experience of added weights or forces when handling objects (Amemiya and Maeda, 2008). These effects can be achieved by creating artificial sensorimotor loops that provide the tactile feedback that the body would experience if the stimuli were present. Virtual compliance illusions have been demonstrated in various contexts, for example when using a pen (Kildal, 2011), fingers (Heo and Lee, 2016), or shoes (Strohmeier et al., 2020); in these various cases, the materials that the pens, fingers, or shoes are pushing against seems to give way. Work has also shown that these principles generalize to the experiences of stretching, bending, and twisting (Heo, Lee and Wigdor, 2019), as well as to more abstract experiences. It is possible to make it seem that objects require more effort to move, or that there are better and worse directions to move them in. These experiences are difficult to describe because standardized language for them has not yet crystallized.

In addition to creating different sensations, the sensorimotor coupling can also be manipulated to change the quality of interaction. For example, when objects are augmented with vibrotactile actuators, the experience of interacting with them can change. A smooth surface can feel like it has many different textures when one passes across its surface a pen that has been actuated to move about in the hand (Romano and Kuchenbecker, 2012). Similarly, a specially designed device that is physically flexible, such as a rod or a cell phone, can be programmed to feel different ways when it bends (Strohmeier et al., 2016). Finally, these motion-coupled vibrotactile patterns can be parameterized, enabling the design of material experiences (Strohmeier and Hornbæk, 2017; Strohmeier et al., 2020). If you make the same movement twice, you get the same pattern twice. If you move differently, you get a different pattern. These haptic patterns can be created using physical models, or they can be created by choosing properties and adjusting them to create specific tactile experiences.

3.3.2 Using perception to change behavior

Existing sensorimotor loops can be subtly modified to change user behavior. Walking in a straight line requires visual input, as we are poor judges of direction based on proprioception alone. As noted above, this fact can be used for creating large virtual spaces in VR. By adjusting the visual feedback while a participant is walking, they can be made to experience large spaces (Razzaque, Kohn and Whitton, 2005; Steinicke et al., 2009). This kind of redirected walking has inspired further experiments that focus on users' sensations when they exit a virtual reality environment and re-enter ordinary reality; it is possible to deliberately rotate the virtual visual field so that when a user removes the VR headset, they are facing a direction opposite to the one they thought they would be facing (Knibbe et al., 2018).

A variation of this theme is haptic retargeting (Zhao and Follmer, 2018), which is used to provide users with haptically rich virtual reality with minimal physical instrumentation. One might provide visual input that does not align with the actual position of a user's hands, to make the user believe that they are stacking multiple blocks atop one another, when in fact, only a single physical block is touched (Azmandian et al., 2016). The movement of the fingers can also be adjusted to resize the user's grasp to fit the physical object, even if the virtual object is smaller or larger (Bergström, Mottelson and Knibbe, 2019).

Because visual stimuli are more reliable than proprioception (Knill and Pouget, 2004), these manipulations go unnoticed by the user. The result is that the user adapts to the modified sensory information and changes their movements accordingly.

3.3.3 Influencing human cognition

A fascinating feature of sensorimotor loops is the interplay between mental and physical states. It is well understood that one can partly infer cognitive states based on body pose and movement, for example identifying unhappiness based on gait patterns (Michalak et al., 2009). More abstract cognition, too, manifests in physical behavior. Because people hesitate for a moment before lying, machine learning algorithms can pick out responses that are almost certainly true (Mottelson, Knibbe and Hornbæk, 2018). Not only does cognition influence behavior, but behavior also influences cognition. One study found that rotating one's hands improves performance on mental rotation tasks (Chu and Kita, 2008). Another study found that turning one's body facilitates imagined turning: if asked at what angle a path turned, people can give more precise answers if they turn their body the way their body would turn if they were physically walking the path (Klatzky et al., 1998). The connection between movement and cognition however is complex, and more movement is not always better. Dancers, for example, typically "mark" when learning a new dance routine. Marking is a movement reduction strategy that dancers use to practice without fully performing a new routine. Studies have shown that this reduced movement strategy improves performance more than practicing the full choreography or pure mental practice (Kirsh, 2013).

Research on body-based user interfaces has raised the question of the extent to which it is possible to influence perceptual loops such as described in the facial feedback hypothesis to influence cognitive states. The seminal study by Strack et al. (1988) showed that activating or inhibiting the muscles involved in smiling, influenced how funny participants rated cartoons. However, replication attempts have been inconclusive (Wagenmakers et al., 2016). Nevertheless, the idea that cognitive states might be influenced in this way has led to systems that require users to smile when operating them to increase user happiness (Tsujita and Rekimoto, 2011; Yen-Chin et al., 2017), as well as to systems that seek to use expansive body poses to manipulate the creativity of responses (Rooij and Jones, 2015) or risk-taking behavior (Jansen and Hornbæk, 2018). It should be noted that the effectiveness of such systems is unclear (Mottelson and Hornbæk, 2020) and a rigorous evaluation of the user interface meant to influence risk-taking behavior found that the user's pose had no effect (Jansen and Hornbæk, 2018).

In conclusion, while there are bidirectional feedback loops between cognitive and physical states, effective ways of using them for HCI purposes are currently missing.

3.4 The experiential body

The fourth view we discuss considers the body as that which experiences not only the world, but also itself. Such a view emphasizes the experiential body comprising the aspects of the body we notice when "turning inwards" (Höök et al., 2015) as it is our body that provides access to its own introspective experience. Research inspired by this view asserts that our bodies are not just material, not just morphological, and not just supporting action-perception loops for interacting with the world. In Heideggerian terms, this view is a reflection of "Leib," the lived experience of being a body in the world, in contrast to "Körper," the material substance a body is made of (Carman, 1999; Mueller et al., 2020b); some work in this vein speaks of "the lived body" (Svanæs, 2013; Dijk, 2018; Mueller et al., 2018). Theoretically, much work inspired by this view draws on the fields of phenomenology (Dourish, 2004; Svanaes and Solheim, 2016) and somaesthetics (Höök, 2018).

Let us consider three representative body-based user interfaces that modify the experience of one's body. First, Kasahara, Nishida and Lopes (2019; Kasahara et al., 2021) explored the timing of electric muscle stimulation (Figure 4, left). They showed that it is possible to time the movement induced by electrical muscle stimulation so that the user not only reacts faster than normal, but also has the feeling that they initiated the motion. Thus, in contrast to much other work that has explored interaction opportunities made available through electrical muscle stimulation, this work emphasizes that EMS can be used not only influence our body movement, but also to design how we experience our actions, in the sense that the way the stimulation is applied changes our perception of what happened. Second, created an illusion that a 3D virtual arm projected out of a person's shoulder (Figure 4, middle). They showed how the user's sense of ownership shifted away from the real arm and toward the virtual arm. Finally, Tajadura-Jiménez et al. (2015) showed that changing the sound of one's footsteps affects the body's perceived weight. They constructed a shoe that, in real-time, uses a change in the frequency spectra to modify the sounds of walking (Figure 4, right). Those sounds produce the sensation, in the wearer, of having either a lighter or heavier body.

In these cases, the user interfaces change the experience of the body. Each of these examples represents a different stream of work. Next, we discuss the progress that has been made within each stream and the aspirations that researchers have for each one.

Figure 4: Body-based user interfaces that highlight or modify the experience of having a body. Left: Movements initiated through electrical muscle stimulation, when timed right, can be experienced as self initiated (Kasahara, Nishida and Lopez, 2019). Middle: An experience of having a virtual arm (Slater et al., 2008). Right: A shoe that changes its wearer's perception of weight (Tajadura-Jiménez et al., 2015).

3.4.1 Feeling in control of the body

Body-based user interfaces can change our experience of control over our actions and our bodies. One key finding has been that different interfaces impact our experience of control differently. When we believe events to be causally related, we underestimate the time between them. This phenomenon is called intentional binding and has been used to study perceived agency when using various interfaces. Results suggest that interfaces on the body, as when the skin is used for touch input as described above, increase agency compared to interfaces that are external to the body, such as a button or a touchpad (Coyle et al., 2012; Bergström-Lehtovirta et al., 2018).

Even more remarkably, we have also seen ways in which technologies can take control of our bodies without impacting our experience of control. For example, Kasahara, Nishida and Lopes (2019) and Kasahara et al. (2021) suggested that, using the tight temporal bounds of perception across intention-action-effect couplings (i.e., planning to do something, doing it, and perceiving the outcome), muscle stimulation could improve our physical reaction times without negatively impacting the sense that we were controlling our actions (see Figure 4). Thus, our experience of control of the body may be fundamentally reshaped by body-based user interfaces.

3.4.2 Feeling ownership of the body

Body-based user interfaces may also change what is experienced as the body and its boundaries. Makin, Vignemont and Faisal (2017) have discussed how digital tools could offer "the ability to process information through external objects at the sensory, motor, or affective levels in the same way as the properties of one's own body parts." The classic example of such an effect is the so-called rubber-hand illusion, where a participant is tricked into thinking that a rubber hand is the participant's actual hand. For body-based user interfaces, the most well-known example is body ownership in virtual reality. In this illusion, ownership is experienced of an avatar that moves in synchronicity with the user

(Slater et al., 2009). This is an extension of the illusion shown in Figure 4 because it concerns the entire body.

Numerous studies have repeated variants of this effect to induce ownership over a variety of bodies in virtual reality. It appears that people can feel ownership of multiple arms (Won et al., 2015), virtual animals of different kinds (Krekhov, Cmentowski and Krüger, 2018), objects (Schettler, Raja and Anderson, 2019), and even invisible bodies (Kondo et al., 2018).

3.4.3 Enhancing the awareness of the body

Body-based user interfaces have aimed to enhance the awareness of the body. The basic idea behind such interfaces is captured by Leigh et al. (2017). They wrote that a user interface not only supports a task "but also changes the way we perceive ourselves and the body's functionalities." This is not about sensing the world, which was discussed in the previous section, but about the feeling of what happens in our body, including its temperature, pain, hunger, nausea, heart rate, and so on.

One approach has been to draw attention to various aspects of the body. Höök et al. (2015), for instance, developed the SomaMat, a technology aims to deepen the users' experience of their bodily sensations by using heat to guide their attention to different body parts. As another example, a recent review suggested that body-based user interfaces can help improve the experience of breathing (Prpa et al., 2020).

4 | Discussion

We have presented a set of four views to help understand the promises and current state of body-based user interfaces. Next, we discuss the status of the four views, how to design technology for the body, and when such user interfaces should be preferred over standard ones.

4.1 How to view the body as a user interface

The views presented here are intended as an analytical tool for thinking about interfaces and about what an interface might reveal of the underlying implicit or explicit views of the body. These views are also not mutually exclusive. A given technology might be analyzed using any of the four views introduced here. Doing so may reveal open questions or point toward directions that deserve further investigation. For example, we have introduced MetaArms by Saraiji et al. (2018) in the context of the morphological body. This best reflects the strength of their work, as they present a wearable system that allows users to manipulate the world with four arms. MetaArms might also be construed from a sensorimotor perspective to look at adaptations in the control of the arms. The work might also be viewed from an experiential perspective. In our experience, and based on personal communication with the authors, one can also use the system while walking. However, as the movement of the third and fourth arm is coupled to the movement of the feet, this completely changes bodily awareness. Finally, MetaArms are attached to and supported by the user, so they also concern the physical body.

The four views are far from exhaustive. Other views include seeing bodies as social and as diverse, views that require designers and engineers to evaluate the acceptability of technology in its intended context of use (Koelle, Ananthanarayan and Boll, 2020). Also, designers and engineers building body-based user interfaces need to be aware of the strong individual differences among bodies. This has pragmatic consequences, ranging from simple issues such as the comfortable fit of an exoskeleton to more complex problems such as the amount and distribution of fatty tissue requiring adjustments of calibration procedures when using EMS. Furthermore, gender, race, and identity are intrinsically connected with the body. When we design for the body, this connection challenges assumptions that may seem straightforward and uncontroversial; however, it also allows us to design technology that positively impact the range of personal and cultural phenomena connected with the body. For an in-depth discussion of this topic, we refer to the review by Spiel (2021). These considerations should not be thought of as additional views next to the ones presented here; rather, they are orthogonal and relevant to all the views of body-based UIs that we have discussed.

4.2 Designing for the body

All the user interfaces we have discussed are the result of design processes, where researchers, designers, and artists create prototypes of how the body may blend with technology. They all raise questions about how one should design body-based user interfaces.

An open issue around such questions is that we lack design languages for a number of design issues relating to the body. For instance, what are the main questions for the design of on-skin interfaces? What are the primitives–the basic, foundational elements – that we may draw upon in interaction design? What are typical solutions to feedback? The answers we have for these questions are not nearly as good as the answers we have for the design of smartphone apps, where there are well established design guidelines, prototypical solutions, and best practices (e.g., Apple, 2019; Google, 2019). Similar questions could be raised for how to interact with implants or how to leverage bodily functions in the UI beyond tracking them. In future work, we would like to see more design explorations of these questions as well as syntheses among point designs to establish design languages and catalogs of design options. The motivation of the papers by Klemmer et al. (2006) and Svanæs (2013) was to provide implications for design. However, they offer either very general principles (such as designing for risk (Klemmer, Hartmann and Takayama, 2006)) or detailed designs (such as Svanæs's examples of page turning or scrolling (Svanaes and Solheim, 2016)). Svanæs's examples appears too detailed to be easily generative in other settings, whereas the idea of risk in Klemmer, Hartmann and Takayama (2006) is too high-level to guide specific decisions when designing interaction. Höök and Löwgren (2012) suggested a middle ground between the two called strong concepts. Strong concepts describe knowledge that is not quite as detailed as a particular artifact and not quite as general as a theory. A strong concept suggests how to design an artifact (is generative) but still considers interaction (i.e., the use context, the behavior over time). In papers on body-based UIs, such concepts – similar to Höök and Lövgren's examples of social navigation and seamfulness (Höök and Löwgren, 2012) – are rare.

Examples from the literature are affective loops (Höök, 2008), guidelines for movement-based games (Mueller and Isbister, 2014), and concepts for sharing other people's bodies (Mitchell et al., 2017).

In future research, we would like to see more strong concepts for body-based UIs.

4.3 When (not) to use body-based UIs

An important question about body-based UIs is when they are preferable to conventional UIs. Where HCI textbooks provide pros and cons for a variety of conventional UIs (e.g., Shneiderman, 2010), the question is much more difficult to answer for body-based UIs. One reason is that many authors who discuss using the body for interaction are often solely positive about the prospects and value of doing so. The paper by Klemmer and colleagues (2006) – one of the most influential papers on the body in HCI – presented dimensions that may be used for evaluation and that might identify cases where a body-based UI is a bad idea. It does not, however, give examples of when a non-body-based UI would be better than a body-based UI. Other papers are similarly silent about the drawbacks of body-based UIs (e.g., Kirsh, 2013; Hummels and Van Dijk, 2015).

A way to address the question about when to use body-based UIs is to identify reasons why people choose body-based UIs. Studies of such choices may help identify and characterize situations where body-based UIs would be preferable and where not. Heffernan, Vetere and Chang (2016) studied why people chose implanted devices and found reasons including "wanting to be part of the next big thing" (p. 1805), extending capabilities, and avoiding what is seen as the burdensomeness of wearables. The Heffernan paper, interestingly, does not list effectiveness as a main motivation for implanted devices. In future work, we would like to see more end-user motivations for using or for not using body-based UIs.

A reason why we do not have a good answer for when to use body-based user interfaces is that the field may not be mature enough to answer this question yet. For example, HCI still tends to focus on performance metrics in comparative interface evaluations, which might not actually measure relevant concepts for judging body-based user interfaces. For instance, we have known for years that mid-air pointing is less effective than using a touch surface (e.g., (Markussen, Jakobsen and Hornbæk, 2014)). But in some situations, other factors, such as the cost of movement (Jakobsen et al., 2015), may outweigh those performance detriments, leading users to choose the less effective UI to reduce the need to move. As traditional HCI studies do not capture such effects, such comparisons have largely been avoided by proponents of body-based user interfaces.

Based on our analysis of the potential future developments of body-based UIs, we see many open issues or trade-offs that may impact the usefulness of body-based UIs. For example (a) the directness of control and experience of body-based UIs may lead to a lack of symbolic communication. This might make them less versatile than, for example, a keyboard, which supports all manner of symbolic input. (b) While the body has countless degrees of freedom, it is unclear what to use them for effectively; the body might dance wonderfully, but wonderful dance can't compose an email. (c) There is a danger of relying too strongly on ideas from embodied psychology that might not have the intended effect, or any effects at all with regards to interacting with computers. (d) With increasingly intimate connections between systems and bodies, small differences between bodies require increased attention, to ensure full functionality. It may therefore pose difficult to scale systems so they can accommodate any body shape or size. Finally, (e) systems with shared control over the user's body lead to both complicated ethical issues as well as a potentially undesirable user experience of lacking control.

5 | Conclusion

A range of research prototypes have emerged over the past decades where input and output occur on and in bodies, and the separation between user and interface has, in some cases, begun to fade away. We have described these cases as body-based user interfaces and described four different views of them. Each view has different potentials and taps different aspects of the body and its special properties. As discussed, such interfaces build on, and raise many questions for, scholarship about the body. They also showcase how human abilities rather than mere technological possibilities can drive how we will interact with computers in the future.

Related topics

Bodily Skill, Peripersonal space (PPS), Tool use, Distal touch and the sensational model, A Plastic Virtual Self: How Virtual Reality Can Be Transforming

References

Al Maimani, A. and Roudaut, A. (2017) "Frozen suit: Designing a changeable stiffness suit and its application to haptic games," in *Proceedings of the 2017 CHI conference on human factors in computing systems*. New York, NY, USA: Association for Computing Machinery (CHI '17), pp. 2440–2448. doi: 10.1145/3025453.3025655.

Amemiya, T. and Maeda, T. (2008) "Asymmetric oscillation distorts the perceived heaviness of handheld objects," *IEEE Transactions on Haptics*, 1(1), pp. 9–18. doi: 10.1109/TOH.2008.5.

Apple (2019) "Human Interface Guidelines." https://developer.apple.com/design/human-interface-guidelines/ios/overview/themes/.

Azmandian, M. et al. (2016) "Haptic retargeting: Dynamic repurposing of passive haptics for enhanced virtual reality experiences," in *Proceedings of the 2016 chi conference on human factors in computing systems*. ACM, pp. 1968–1979.

Bergström, J. and Hornbæk, K. (2019) "Human–computer interaction on the skin," *ACM Comput. Surv.*, 52(4), pp. 77:1–77:14. doi: 10.1145/3332166.

Bergström, J., Mottelson, A. and Knibbe, J. (2019) "Resized grasping in VR: Estimating thresholds for object discrimination," in *Proceedings of the 32nd annual ACM symposium on user interface software and technology*. New York, NY, USA: Association for Computing Machinery (UIST '19), pp. 1175–1183. doi: 10.1145/3332165.3347939.

Bergström-Lehtovirta, J. et al. (2018) “I really did that: Sense of agency with touchpad, keyboard, and on-skin interaction,” in *Proceedings of the 2018 CHI conference on human factors in computing systems*. ACM, p. 378.

Bergström-Lehtovirta, J., Boring, S. and Hornbæk, K. (2017) “Placing and recalling virtual items on the skin,” in *Proceedings of the 2017 CHI conference on human factors in computing systems*. ACM, pp. 1497–1507.

Buxton, W. (1994) “Taxonomies of Input,” in *Input Theories, Techniques and Technology*. Available at: http://www.billbuxton.com/inputManuscript.html.

Byrne, R., Marshall, J. and Mueller, F. (2016) “Balance ninja: Towards the design of digital vertigo games via galvanic vestibular stimulation,” in *Proceedings of the 2016 annual symposium on computer-human interaction in play*. ACM, pp. 159–170.

Campo Woytuk, N. et al. (2020) “Touching and being in touch with the menstruating body,” in *Proceedings of the 2020 CHI conference on human factors in computing systems*. New York: Association for Computing Machinery (CHI ’20), pp. 1–14. doi: 10.1145/3313831.3376471.

Card, S.K., Mackinlay, J.D. and Robertson, G.G. (1990) “The design space of input devices,” in *Proceedings of the SIGCHI conference on human factors in computing systems*. New York: Association for Computing Machinery (CHI ’90), pp. 117–124. doi: 10.1145/97243.97263.

Card, S.K., Moran, T.P. and Newell, A. (1983) *The Psychology of Human-Computer Interaction*. CRC Press.

Carman, T. (1999) “The Body in Husserl and Merleau-Ponty,” *Philosophical Topics*, 27(2), pp. 205–226. doi: 10.1177/0959354399091005.

Casadio, M., Ranganathan, R. and Mussa-Ivaldi, F.A. (2012) “The Body-Machine Interface: A New Perspective on an Old Theme,” *Journal of Motor Behavior*, 44(6), pp. 419–433.

Chu, M. and Kita, S. (2008) “Spontaneous gestures during mental rotation tasks: Insights into the microdevelopment of the motor strategy.” *Journal of Experimental Psychology: General*, 137(4), p. 706.

Clarke, F. (1960) “A study of troxler’s effect,” *Optica Acta: International Journal of Optics*, 7(3), pp. 219–236.

Coyle, D. et al. (2012) “I did that! Measuring users’ experience of agency in their own actions,” in *Proceedings of the SIGCHI conference on human factors in computing systems*. ACM, pp. 2025–2034.

Danry, V. et al. (2021) “Do cyborgs dream of electric limbs? Experiential factors in human-computer integration design and evaluation.” In Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems (CHI EA '21). Association for Computing Machinery, New York, NY, USA, Article 123, 1–6. https://doi.org/10.1145/3411763.3441355

Dijk, J. van (2018) “Designing for Embodied Being-in-the-World: A Critical Analysis of the Concept of Embodiment in the Design of Hybrids,” *Multimodal Technologies and Interaction*, 2(1), p. 7. doi: 10.3390/mti2010007.

Dourish, P. (2004) *Where the action is: The foundations of embodied interaction*. MIT Press.

Engelbart, D.C. (1962) “Augmenting human intellect: A conceptual framework,” Menlo Park, CA: Stanford Research Institute.

Fishkin, K.P. (2004) “A taxonomy for and analysis of tangible interfaces,” *Personal and Ubiquitous Computing*, 8(5), pp. 347–358.

Flemings, M. et al. (2018) “Crimson wave: Shedding light on menstrual health,” in *Proceedings of the twelfth international conference on tangible, embedded, and embodied interaction*. New York: ACM (TEI ’18), pp. 343–348. doi: 10.1145/3173225.3173292.

Gonzalez, E.J. and Follmer, S. (2019) “Investigating the detection of bimanual haptic retargeting in virtual reality,” in *25th ACM symposium on virtual reality software and technology*. New York: Association for Computing Machinery (VRST ’19). doi: 10.1145/3359996.3364248.

Google (2019) “Design for Android.” https://developer.android.com/design.

Goto, T. et al. (2018) “Artificial motion guidance: An intuitive device based on pneumatic gel muscle (PGM),” in *31st annual ACM symposium on user interface software and technology adjunct proceedings*. New York: ACM (UIST ’18 adjunct), pp. 182–184. doi: 10.1145/3266037.3271644.

Gustafson, S., Holz, C. and Baudisch, P. (2011) “Imaginary phone: Learning imaginary interfaces by transferring spatial memory from a familiar device,” in *Proceedings of the 24th annual ACM symposium on user interface software and technology*. ACM, pp. 283–292.

Harrison, C., Benko, H. and Wilson, A.D. (2011) “OmniTouch: Wearable multitouch interaction everywhere,” in *Proceedings of the 24th annual ACM symposium on user interface software and technology*. ACM, pp. 441–450.

Harrison, C., Tan, D. and Morris, D. (2010) “Skinput: Appropriating the body as an input surface,” in *Proceedings of the SIGCHI conference on human factors in computing systems*. New York: ACM (CHI ’10), pp. 453–462. doi: 10.1145/1753326.1753394.

Harrison, I., Warwick, K. and Ruiz, V. (2018) “Subdermal magnetic implants: An experimental study,” *Cybernetics and Systems*, 49(2), pp. 122–150. doi: 10.1080/01969722.2018.1448223.

Hartman, K. et al. (2015) “Monarch: Self-expression through wearable kinetic textiles,” in *Proceedings of the ninth international conference on tangible, embedded, and embodied interaction*. New York: ACM (TEI ’15), pp. 413–414. doi: 10.1145/2677199.2690875.

Hattwick, I., Malloch, J.W. and Wanderley, M.M. (2014) “Forming shapes to bodies: Design for manufacturing in the prosthetic instruments,” in *NIME*, pp. 443–448.

Heffernan, K.J., Vetere, F. and Chang, S. (2016) “You put what, where?: Hobbyist use of insertable devices,” in *Proceedings of the 2016 CHI conference on human factors in computing systems*. New York: ACM (CHI ’16), pp. 1798–1809. doi: 10.1145/2858036.2858392.

Heo, S. and Lee, G. (2016) “Vibrotactile compliance feedback for tangential force interaction,” *IEEE Transactions on Haptics*, 10(3), pp. 444–455.

Heo, S., Lee, J. and Wigdor, D. (2019) “PseudoBend: Producing haptic illusions of stretching, bending, and twisting using grain vibrations,” in *Proceedings of the 32nd annual ACM symposium on user interface software and technology*. New York: Association for Computing Machinery (UIST ’19), pp. 803–813. doi: 10.1145/3332165.3347941.

Holz, C. et al. (2012) “Implanted user interfaces,” in *Proceedings of the SIGCHI conference on human factors in computing systems*. New York: ACM (CHI ’12), pp. 503–512. doi: 10.1145/2207676.2207745.

Homewood, S., Bewley, H. and Boer, L. (2019) “Ovum: Designing for fertility tracking as a shared and domestic experience,” in *Proceedings of the 2019 on designing interactive systems conference*.

New York: ACM (DIS ’19), pp. 553–565. doi: 10.1145/3322276.3323692.

Höök, K. (2008) “Affective loop experiences–what are they?” in *International conference on persuasive technology*. Springer, pp. 1–12.

Höök, K. et al. (2015) “Cover story somaesthetic design,” *Interactions*, 22(4), pp. 26–33.

Höök, K. et al. (2017) “Soma-based design theory,” in *Proceedings of the 2017 CHI conference extended abstracts on human factors in computing systems*. New York: Association for Computing Machinery (CHI EA ’17), pp. 550–557. doi: 10.1145/3027063.3027082.

Höök, K. (2018) *Designing with the Body: Somaesthetic interaction design*. MIT Press.

Höök, K. and Löwgren, J. (2012) “Strong concepts: Intermediate-level knowledge in interaction design research,” *ACM Transactions on Computer-Human Interaction (TOCHI)*, 19(3), p. 23.

Huber, J. et al. (2018) *Assistive Augmentation*. Springer.

Hummels, C. and Van Dijk, J. (2015) “Seven principles to design for embodied sensemaking,” in *Proceedings of the ninth international conference on tangible, embedded, and embodied interaction*. ACM, pp. 21–28.

Jakobsen, M.R. et al. (2015) “Should I stay or should I go? Selecting between touch and mid-air gestures for large-display interaction,” in *IFIP conference on human-computer interaction*. Springer, pp. 455–473.

Jansen, Y. and Hornbæk, K. (2018) “How relevant are incidental power poses for HCI?” in *Proceedings of the 2018 CHI conference on human factors in computing systems*. New York: ACM (CHI ’18), pp. 14:1–14:14. doi: 10.1145/3173574.3173588.

Kao, H.-L. (Cindy). (2017) “Hybrid body craft,” in *Proceedings of the 2017 ACM conference companion publication on designing interactive systems*. New York: Association for Computing Machinery (DIS ’17 companion), pp. 391–392. doi: 10.1145/3064857.3079167.

Kasahara, S. et al. (2021) “Preserving agency during electrical muscle stimulation training speeds up reaction time directly after removing EMS,” in *Proceedings of the 2021 CHI conference on human factors in computing systems*. New York: Association for Computing Machinery (CHI ’21). doi: 10.1145/3411764.3445147.

Kasahara, S., Nishida, J. and Lopes, P. (2019) “Preemptive action: Accelerating human reaction using electrical muscle stimulation without compromising agency,” in *Proceedings of the 2019 CHI conference on human factors in computing systems*. New York: ACM (CHI ’19), pp. 643:1–643:15. doi: 10.1145/3290605.3300873.

Kildal, J. (2011) “Tangible 3D haptics on touch surfaces: Virtual compliance,” in *CHI ’11 extended abstracts on human factors in computing systems*. New York: Association for Computing Machinery (CHI EA ’11), pp. 1123–1128. doi: 10.1145/1979742.1979717.

Kilteni, K. et al. (2015) “Over my fake body: Body ownership illusions for studying the multisensory basis of own-body perception,” *Frontiers in Human Neuroscience*, 9, p. 141. doi: 10.3389/fnhum.2015.00141.

Kim, D.-H. et al. (2011) “Epidermal electronics,” *Science*, 333(6044), pp. 838–843. doi: 10.1126/science.1206157.

Kirkham, A. et al. (2002) “Neuromodulation through sacral nerve roots 2 to 4 with a finetech-brindley sacral posterior and anterior root stimulator," *Spinal Cord*, 40(6), pp. 272–281.

Kirsh, D. (2013) "Embodied cognition and the magical future of interaction design," *ACM Transactions on Computer-Human Interaction (TOCHI)*, 20(1), p. 3.

Klatzky, R.L. et al. (1998) "Spatial updating of self-position and orientation during real, imagined, and virtual locomotion," *Psychological Science*, 9(4), pp. 293–298.

Klemmer, S.R., Hartmann, B. and Takayama, L. (2006) "How bodies matter: Five themes for interaction design," in *Proceedings of the 6th conference on designing interactive systems*. ACM, pp. 140–149.

Knibbe, J. et al. (2017) "Automatic calibration of high density electric muscle stimulation," *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.*, 1(3), pp. 68:1–68:17. doi: 10.1145/3130933.

Knibbe, J. et al. (2018) "The dream is collapsing: The experience of exiting VR," in *Proceedings of the 2018 CHI conference on human factors in computing systems*. New York: Association for Computing Machinery (CHI '18), pp. 1–13. doi: 10.1145/3173574.3174057.

Knibbe, J. et al. (2021) "Skill-sleeves: Designing electrode garments for wearability," in *Proceedings of the fifteenth international conference on tangible, embedded, and embodied interaction*. New York: Association for Computing Machinery (TEI '21). doi: 10.1145/3430524.3440652.

Knill, D.C. and Pouget, A. (2004) "The Bayesian brain: the role of uncertainty in neural coding and computation," *Trends in Neurosciences*, 27(12), pp. 712–719. doi: 10.1016/J.TINS.2004.10.007.

Koelle, M., Ananthanarayan, S. and Boll, S. (2020) "Social acceptability in HCI: A survey of methods, measures, and design strategies," in *Proceedings of the 2020 CHI conference on human factors in computing systems*. New York: Association for Computing Machinery (CHI '20), pp. 1–19. doi: 10.1145/3313831.3376162.

Kondo, R. et al. (2018) "Illusory body ownership of an invisible body interpolated between virtual hands and feet via visual-motor synchronicity," *Scientific Reports*, 8(1), pp. 1–8.

Krekhov, A., Cmentowski, S. and Krüger, J. (2018) "VR animals: Surreal body ownership in virtual reality games," in *Proceedings of the 2018 annual symposium on computer-human interaction in play companion extended abstracts*. New York: Association for Computing Machinery (CHI PLAY '18 extended abstracts), pp. 503–511. doi: 10.1145/3270316.3271531.

Laha, B. et al. (2016) "Evaluating control schemes for the third arm of an avatar," *Presence: Teleoper. Virtual Environ.*, 25(2), pp. 129–147. doi: 10.1162/PRES_a_00251.

Leigh, S. et al. (2017) "Body-borne computers as extensions of self," *Computers*, 6(1), p. 12.

Leigh, S. (2018) *Robotic SYmbionts – Exploring Integrated Human-Machine Action and Expression Signature redacted Signature redacted*. PhD thesis. Massachusetts Institute of Technology.

Leigh, S. and Maes, P. (2016) "Body integrated programmable joints interface," in *Proceedings of the 2016 CHI conference on human factors in computing systems*. New York: ACM (CHI '16), pp. 6053–6057. doi: 10.1145/2858036.2858538.

Leigh, S. and Maes, P. (2017) "Morphological interfaces: On body transforming technologies," in *Proceedings of the 2017 CHI conference extended abstracts on human factors in computing systems*. New York: ACM (CHI EA '17), pp. 896–906. doi: 10.1145/3027063.3052758.

Leigh, S. and Maes, P. (2018) "Guitar machine: Robotic fretting augmentation for hybrid human-machine guitar play." in *NIME*, pp. 403–408.

Li, Z. et al. (2019) "HeatCraft: Designing playful experiences with ingestible sensors via localized thermal stimuli," in *Proceedings of the 2019 CHI conference on human factors in computing systems*. New York: ACM (CHI '19), pp. 576:1–576:12. doi: 10.1145/3290605.3300806.

Licklider, J.C. (1960) "Man-computer symbiosis," *IRE transactions on human factors in electronics*, (1), pp. 4–11.

Loke, L. and Robertson, T. (2011) "The lived body in design: Mapping the terrain," in *Proceedings of the 23rd Australian computer-human interaction conference*. New York: Association for Computing Machinery (OzCHI '11), pp. 181–184. doi: 10.1145/2071536.2071565.

Lopes, P. et al. (2015) "Proprioceptive interaction," in *Proceedings of the 33rd annual ACM conference on human factors in computing systems*. New York: ACM (CHI '15), pp. 939–948. doi: 10.1145/2702123.2702461.

Lopes, P. et al. (2016) "Muscle-plotter: An interactive system based on electrical muscle stimulation that produces spatial output," in *Proceedings of the 29th annual symposium on user interface software and technology*. New York: Association for Computing Machinery (UIST '16), pp. 207–217. doi: 10.1145/2984511.2984530.

Lopes, P. et al. (2017) "Providing haptics to walls & heavy objects in virtual reality by means of electrical muscle stimulation," in *Proceedings of the 2017 CHI conference on human factors in computing systems*. New York: ACM (CHI '17), pp. 1471–1482. doi: 10.1145/3025453.3025600.

Lopes, P., Jonell, P. and Baudisch, P. (2015) "Affordance++: Allowing objects to communicate dynamic use," in *Proceedings of the 33rd annual ACM conference on human factors in computing systems*. New York: ACM (CHI '15), pp. 2515–2524. doi: 10.1145/2702123.2702128.

Maekawa, A. et al. (2020) "Dynamic motor skill synthesis with human-machine mutual actuation," in *Proceedings of the 2020 CHI conference on human factors in computing systems*. New York: Association for Computing Machinery (CHI '20), pp. 1–12. doi: 10.1145/3313831.3376705.

Maes, P. et al. (1997) "The ALIVE system: Wireless, full-body interaction with autonomous agents," *Multimedia Systems*, 5(2), pp. 105–112.

Makin, T.R., de Vignemont, F. and Faisal, A.A. (2017) "Neurocognitive barriers to the embodiment of technology," *Nature Biomedical Engineering*, 1(1), pp. 1–3.

Markussen, A., Jakobsen, M.R. and Hornbæk, K. (2014) "Vulture: A mid-air word-gesture keyboard," in *Proceedings of the SIGCHI conference on human factors in computing systems*. New York: ACM (CHI '14), pp. 1073–1082. doi: 10.1145/2556288.2556964.

Matthew, R.P. et al. (2015) "Optimal design for individualised passive assistance," in *Proceedings of the 6th augmented human international conference*. New York: Association for Computing Machinery (AH '15), pp. 69–76. doi: 10.1145/2735711.2735793.

Maynes-Aminzade, D. and Raffle, H. (2003) "You're in control: A urinary user interface," in *CHI '03 extended abstracts on human factors in computing systems*. New York: ACM (CHI EA '03), pp. 986–987. doi: 10.1145/765891.766108.

McIntosh, J. et al. (2019) "Magnetips: Combining fingertip tracking and haptic feedback for around-device interaction," in *Proceedings of the 2019 CHI conference on human factors in computing systems*. New York: ACM (CHI '19), pp. 408:1–408:12. doi: 10.1145/3290605.3300638.

McIntosh, J. et al. (2020) "Iteratively Adapting Avatars using Task-Integrated Optimisation," in *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*. Association for Computing Machinery, New York: ACM (UIST'20), pp. 709–721. doi: 10.1145/3379337.3415832

Michalak, J. et al. (2009) "Embodiment of sadness and depression – gait patterns associated with dysphoric mood," *Psychosomatic Medicine*, 71(5), pp. 580–587.

Milne, A.P., Antle, A.N. and Riecke, B.E. (2011) "Tangible and body-based interaction with auditory maps," in *CHI'11 extended abstracts on human factors in computing systems*, pp. 2329–2334.

Mitchell, R. et al. (2017) "We-coupling!: Designing new forms of embodied interpersonal connection," in *Proceedings of the eleventh international conference on tangible, embedded, and embodied interaction*. New York: ACM (TEI '17), pp. 775–780. doi: 10.1145/3024969.3025051.

Mottelson, A. and Hornbæk, K. (2020) "Emotional avatars: The interplay between affect and ownership of a virtual body," *arXiv preprint arXiv:2001.05780*.

Mottelson, A., Knibbe, J. and Hornbæk, K. (2018) "Veritaps: Truth estimation from mobile interaction," in *Proceedings of the 2018 CHI conference on human factors in computing systems*. New York: ACM (CHI '18), pp. 561:1–561:12. doi: 10.1145/3173574.3174135.

Mueller, F.F. et al. (2018) "Experiencing the body as play," in *Proceedings of the 2018 CHI conference on human factors in computing systems*. New York: Association for Computing Machinery, pp. 1–13. Available at: https://doi.org/10.1145/3173574.3173784.

Mueller, F.F. et al. (2020a) "Next steps for human-computer integration," in *Proceedings of the 2020 CHI conference on human factors in computing systems*. New York: Association for Computing Machinery, pp. 1–15. Available at: https://doi.org/10.1145/3313831.3376242.

Mueller, F.F. et al. (2020b) "'Erfahrung & Erlebnis': Understanding the bodily play experience through german lexicon," in *Proceedings of the fourteenth international conference on tangible, embedded, and embodied interaction*. New York: Association for Computing Machinery (TEI '20), pp. 337–347. doi: 10.1145/3374920.3374926.

Mueller, F. and Isbister, K. (2014) "Movement-based game guidelines," in *Proceedings of the SIGCHI conference on human factors in computing systems*. New York: ACM (CHI '14), pp. 2191–2200. doi: 10.1145/2556288.2557163.

Nabeshima, J., Saraiji, M. Y. and Minamizawa, K. (2019) "Arque: Artificial biomimicry-lnspired tail for extending innate body functions," in *ACM SIGGRAPH 2019 emerging technologies*. New York: ACM (SIGGRAPH '19), pp. 8:1–8:2. doi: 10.1145/3305367.3327987.

Nishida, J. and Suzuki, K. (2017) "bioSync: A paired wearable device for blending kinesthetic experience," in *Proceedings of the 2017 CHI conference on human factors in computing systems*. New York: ACM (CHI '17), pp. 3316–3327. doi: 10.1145/3025453.3025829.

Perkins, T.A. et al. (2002) "Control of leg-powered paraplegic cycling using stimulation of the lumbo-sacral anterior spinal nerve roots," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 10(3), pp. 158–164.

Pfeiffer, M. et al. (2015) "Cruise control for pedestrians: Controlling walking direction using electrical muscle stimulation," in *Proceedings of the 33rd annual ACM conference on human factors in computing systems*. New York: ACM (CHI '15), pp. 2505–2514. doi: 10.1145/2702123.2702190.

Pohl, H., Hoheisel, F. and Rohs, M. (2017) "Inhibiting freedom of movement with compression feedback," in *Proceedings of the 2017 CHI conference extended abstracts on human factors in computing systems*. New York: Association for Computing Machinery (CHI EA '17), pp. 1962–1969. doi: 10.1145/3027063.3053081.

Pohl, H. and Hornbæk, K. (2018) "ElectricItch: Skin irritation as a feedback modality," in *Proceedings of the 31st annual ACM symposium on user interface software and technology*. New York: ACM (UIST '18), pp. 765–778. doi: 10.1145/3242587.3242647.

Pons, J.L. (2010) "Rehabilitation exoskeletal robotics," *IEEE Engineering in Medicine and Biology Magazine*, 29(3), pp. 57–63.

Pourjafarian, N. et al. (2021) "BodyStylus: Freehand on-body design and fabrication of epidermal interfaces." In Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21). Association for Computing Machinery, New York, NY, USA, Article 504, 1–15. doi: 10.1145/3411764.3445475

Prpa, M. et al. (2020) "Inhaling and exhaling: How technologies can perceptually extend our breath awareness," in *Proceedings of the 2020 CHI conference on human factors in computing systems*. New York: Association for Computing Machinery (CHI '20), pp. 1–15. doi: 10.1145/3313831.3376183.

Razzaque, S., Kohn, Z. and Whitton, M.C. (2005) *Redirected walking*. Citeseer.

Reed, C.N. and McPherson, A.P. (2021) "Surface electromyography for sensing performance intention and musical imagery in vocalists," in *Proceedings of the fifteenth international conference on tangible, embedded, and embodied interaction*. New York: Association for Computing Machinery (TEI '21). doi: 10.1145/3430524.3440641.

Riener, R. (2016) "The cybathlon promotes the development of assistive technology for people with physical disabilities," *Journal of Neuroengineering and Rehabilitation*, 13(1), pp. 1–4.

Romano, J.M. and Kuchenbecker, K.J. (2012) "Creating realistic virtual textures from contact acceleration data," *IEEE Transactions on Haptics*, 5(2), pp. 109–119. doi: 10.1109/TOH.2011.38.

Rooij, A. de and Jones, S. (2015) "(E)motion and creativity: Hacking the function of motor expressions in emotion regulation to augment creativity," in *Proceedings of the ninth international conference on tangible, embedded, and embodied interaction*. New York: Association for Computing Machinery (TEI '15), pp. 145–152. doi: 10.1145/2677199.2680552.

Saraiji, M.Y. et al. (2018) "MetaArms: Body remapping using feet-controlled artificial arms," in *Proceedings of the 31st annual ACM symposium on user interface software and technology*. New York: ACM (UIST '18), pp. 65–74. doi: 10.1145/3242587.3242665.

Schettler, A., Raja, V. and Anderson, M.L. (2019) "The embodiment of objects: Review, analysis, and future directions," *Frontiers in Neuroscience*, 13, p. 1332. doi: 10.3389/fnins.2019.01332.

Schraefel, M.C. (2020) "Introduction," *Interactions*, 27(2), pp. 32–37. doi: 10.1145/3380811.

Shanken, E.A. (2009) "Art and Electronic Media," Phaidon Press. doi: 10.5860/choice.47-1805.

Shneiderman, B. (2010) *Designing the User Interface: Strategies for effective human-computer interaction*. Pearson Education India.

Shoemaker, G. et al. (2010) "Body-centric interaction techniques for very large wall displays," in *Proceedings of the 6th nordic conference on human-computer interaction: Extending boundaries*, pp. 463–472.

Slater, M. et al. (2008) “Towards a digital body: The virtual arm illusion,” *Frontiers in Human Neuroscience*, 2, p. 6. doi: 10.3389/neuro.09.006.2008.

Slater, M. et al. (2009) “Inducing illusory ownership of a virtual body,” *Frontiers in Neuroscience*, 3, p. 29.

Spiel, K. (2021) “The bodies of TEI – investigating norms and assumptions in the design of embodied interaction,” in *Proceedings of the fifteenth international conference on tangible, embedded, and embodied interaction*. New York: Association for Computing Machinery (TEI ’21). doi: 10.1145/3430524.3440651.

Steimle, J. (2016) “Skin–the next user interface,” *Computer*, 49(04), pp. 83–87. doi: 10.1109/MC.2016.93.

Steinicke, F. et al. (2009) “Estimation of detection thresholds for redirected walking techniques,” *IEEE transactions on visualization and computer graphics*, 16(1), pp. 17–27.

Stelarc (2020) “Contemporary chimeras: Creepy, uncanny and contestable bodies,” *AHs ’20: Proceedings of the augmented humans international conference*. New York: Association for Computing Machinery.

Stevens, J.K. et al. (1976) “Paralysis of the awake human: Visual perceptions,” *Vision Research*, 16(1), pp. 93–IN9. doi: 10.1016/0042-6989(76)90082-1.

Strack, F., Martin, L.L. and Stepper, S. (1988) “Inhibiting and facilitating conditions of the human smile: A nonobtrusive test of the facial feedback hypothesis.” *Journal of Personality and Social Psychology*, 54(5), p. 768.

Strohmeier, P. et al. (2016) “ReFlex: A flexible smartphone with active haptic feedback for bend input,” in *Proceedings of the TEI ’16: Tenth international conference on tangible, embedded, and embodied interaction*. New York: Association for Computing Machinery (TEI ’16), pp. 185–192. doi: 10.1145/2839462.2839494.

Strohmeier, P. et al. (2018) “zPatch: Hybrid resistive/capacitive eTextile input,” in *Proceedings of the twelfth international conference on tangible, embedded, and embodied interaction*. New York: ACM (TEI ’18), pp. 188–198. doi: 10.1145/3173225.3173242.

Strohmeier, P. et al. (2020) “BARefoot: Generating virtual materials using motion coupled vibration in shoes,” in *Proceedings of the 33rd annual ACM symposium on user interface software and technology*. New York: Association for Computing Machinery (UIST ’20), pp. 579–593. doi: 10.1145/3379337.3415828.

Strohmeier, P. and Hornbæk, K. (2017) “Generating haptic textures with a vibrotactile actuator,” in *Proceedings of the 2017 CHI conference on human factors in computing systems*. New York: Association for Computing Machinery (CHI ’17), pp. 4994–5005. doi: 10.1145/3025453.3025812.

Strohmeier, P. and McIntosh, J. (2020) “Novel input and output opportunities using an implanted magnet,” in *Proceedings of the augmented humans international conference*. New York: Association for Computing Machinery (AHs ’20). doi: 10.1145/3384657.3384785.

Suchman, L.A. (1987) *Plans and Situated Actions: The problem of human-machine communication*. Cambridge University Press.

Svanaes, D. and Solheim, M. (2016) “Wag your tail and flap your ears: The kinesthetic user experience of extending your body,” in *Proceedings of the 2016 CHI conference extended abstracts on human factors in computing systems*. New York: ACM (CHI EA ’16), pp. 3778–3779. doi: 10.1145/2851581.2890268.

Svanæs, D. (2013) “Interaction design for and with the lived body: Some implications of merleau-ponty’s phenomenology,” *ACM Transactions on Computer-Human Interaction (TOCHI)*, 20(1), p. 8.

Tajadura-Jiménez, A. et al. (2015) “As light as your footsteps: Altering walking sounds to change perceived body weight, emotional state and gait,” in *Proceedings of the 33rd annual ACM conference on human factors in computing systems*. ACM, pp. 2943–2952.

Thomas, G.C., Coholich, J.M. and Sentis, L. (2019) “Compliance shaping for control of strength amplification exoskeletons with elastic cuffs,” in *2019 IEEE/ASME international conference on advanced intelligent mechatronics (AIM)*, pp. 1199–1206. doi: 10.1109/AIM.2019.8868484.

Tsujita, H. and Rekimoto, J. (2011) “Smiling makes us happier: Enhancing positive mood and communication with smile-encouraging digital appliances,” in *Proceedings of the 13th international conference on ubiquitous computing*. New York: Association for Computing Machinery (UbiComp ’11), pp. 1–10. doi: 10.1145/2030112.2030114.

Uexkull, J. von (1934) “A Stroll Through the Worlds of Animal and Men,” in *Instinctive Behavior*, trans, by Claire H. Schiller (ed.), 5-80. Madison, CT: International Universities Press, 1957, pp. 319–391.

Vasisht, D. and Zhang, G. (2019) “In-body devices: The future of medicine,” *XRDS*, 26(1), pp. 32–35. doi: 10.1145/3351476.

Vega, K. and Fuks, H. (2014) “Beauty technology: Body surface computing,” *Computer*, 4, pp. 71–75.

Wagenmakers, E.-J. et al. (2016) “Registered replication report: Strack, martin, & stepper (1988),” *Perspectives on Psychological Science*, 11(6), pp. 917–928.

Wagner, J. et al. (2013) “Body-centric design space for multi-surface interaction,” in *Proceedings of the SIGCHI conference on human factors in computing systems*. ACM, pp. 1299–1308.

Waller, D., Loomis, J.M. and Haun, D.B.M. (2004) “Body-based senses enhance knowledge of directions in large-scale environments,” *Psychonomic Bulletin & Review*, 11(1), pp. 157–163. doi: 10.3758/BF03206476.

Wang, C.-Y. et al. (2015) “PalmType: Using palms as keyboards for smart glasses,” in *Proceedings of the 17th international conference on human-computer interaction with mobile devices and services*. ACM, pp. 153–160.

Watts, I. (2009) “Red ochre, body painting, and language: Interpreting the blombos ochre,” *The Cradle of Language*, 2, pp. 93–129.

Weigel, M. et al. (2015) “iSkin: Flexible, stretchable and visually customizable on-body touch sensors for mobile computing,” in *Proceedings of the 33rd annual ACM conference on human factors in computing systems*. ACM, pp. 2991–3000.

Weigel, M. et al. (2017) “Skinmarks: Enabling interactions on body landmarks using conformal skin electronics,” in *Proceedings of the 2017 CHI conference on human factors in computing systems*. ACM, pp. 3095–3105.

Wigdor, D. and Wixon, D. (2011) *Brave NUI world: Designing natural user interfaces for touch and gesture*. Morgan Kaufmann.

Withana, A., Groeger, D. and Steimle, J. (2018) “Tacttoo: A thin and feel-through tattoo for on-skin tactile output,” in *Proceedings of the 31st annual ACM symposium on user interface software and technology*. New York: ACM (UIST ’18), pp. 365–378. doi: 10.1145/3242587.3242645.

Won, A.S. et al. (2015) "Homuncular flexibility in virtual reality," *Journal of Computer-Mediated Communication*, 20(3), pp. 241–259.

Yen-Chin, L. et al. (2017) "Eyewear to make me smile: Can electric muscle stimulation increase happiness?" in *Proceedings of the eleventh international conference on tangible, embedded, and embodied interaction*. New York: Association for Computing Machinery (TEI '17), pp. 579–582. doi: 10.1145/3024969.3025097.

Zhai, S. (1998) "User performance in relation to 3D input device design," *ACM Siggraph Computer Graphics*, 32. doi: 10.1145/307710.307728.

Zhao, Y. and Follmer, S. (2018) "A functional optimization based approach for continuous 3D retargeted touch of arbitrary, complex boundaries in haptic virtual reality," in *Proceedings of the 2018 CHI conference on human factors in computing systems*. New York: Association for Computing Machinery (CHI '18), pp. 1–12. doi: 10.1145/3173574.3174118.