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Human-Computer Integration: Towards integrating the human body with the computational machine

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Human-Computer Integration (short: HInt) is an emerging new paradigm in the human-computer interaction (HCI) field. Its goal is to integrate the human body and the computational machine. This article presents two key dimensions of Human-Computer Integration (bodily agency and bodily ownership) and proposes a set of challenges that we believe need to be resolved in order to bring the paradigm forward. Ultimately, our work aims to facilitate a more structured investigation into human body and computational machine integration.

Keywords: Human-computer integration, embodiment, augmented human, cyborg, fusion

1. INTRODUCTION: INTEGRATING THE HUMAN BODY WITH THE COMPUTATIONAL MACHINE

There is increasing interest in human-computer interaction via the human-computer integration, or "HInt", paradigm (Mueller, Lopes, et al., 2020). This paradigm is characterized by a move beyond the traditional master-slave relationship between human and computational machine and towards their fusion (Mueller, Lopes, et al., 2020). In this article, we consider this paradigm, focus on a future in which the boundary between human body and computational machine is blurred (Lopes, Ion, et al., 2015), and we identify the key challenges associated with this future. We specifically consider the challenge of discerning which of the user or the computational machine is in control of the fused body, and we note that this ability to fuse and share control might offer new opportunities, including unique user experiences, but it also brings new pitfalls and shortcomings (Mueller, Lopes, et al., 2020).

In this context, we believe it is important to articulate the challenges associated with these developments to help inform, improve and guide future design. In articulating these HInt challenges, we also contend that the HCI field has a responsibility to develop devices that are safe, ethical, and make positive social contributions.

Because HInt is not an isolated area of research, we can draw upon discussions from existing, related perspectives, including cybernetics (Ashby, 1961; Licklider, 1960), augmentation (Engelbart, 1962; Mann, 2001; Raisamo et al., 2019; Rheingold, 2013), cyborgs (Clark, 2001) and wearables (Starner, 2001). However, while these prior works provide a grounding basis for HInt, and some of their associated challenges also apply to HInt, we focus on articulating the HInt challenges that are of particular relevance to HCI because we expect that the HCI field will engage with many HInt related developments in one form or another in the near future.

Prior work has investigated how integration happens at a societal level, whereby computational machines and people coordinate efforts towards a common goal (Mueller, Lopes, et al., 2020). In contrast with this societal emphasis (albeit, without dismissing it), we focus on integration that occurs primarily at the individual level, whereby computational machines provide "information directly to human senses rather than through symbolic representations and understanding the user's implicit, precognitive needs through bio-sensing" (Mueller, Lopes, et al., 2020). In this way, the concern of integration moves beyond the question "*How do we design technology that allows for better interactions with computers*?" to consider the question "*How do we design technology that integrates with the user's body*?" (Mueller, Lopes, et al., 2020).

This article makes three contributions: First, we apply two key dimensions from psychology – bodily agency and bodily ownership – to enhance our understanding of HInt systems (based on (Mueller et al., 2021)). Second, we use these two dimensions to provide new perspectives on user integration experiences and to develop an integration systems design space. Third, we use the design space and its two dimensions to articulate HInt's key challenges (based on (Mueller, Lopes, et al., 2020)), and we group these challenges into four areas: design, society, identity, and technology.

In making these contributions, our aim is to help researchers and designers identify opportunities to contribute to the emerging HInt paradigm. Similarly, we hope that educators can profit from our work because our structured articulation of challenges can help teachers prepare materials for HInt classes, and HCI academics currently not working in the field might find our work to be a useful introduction to recent HInt developments. Our work might also help academics who want to evaluate systems and wish to consider the HInt paradigm's wider implications. We hope that our articulation of HInt challenges also assists interaction designers to solve practical integration development problems and to avoid even bigger ones. Developers might use our work to guide them when identifying the capabilities required for engineering future systems, and developing training. We also hope that our work could help students understand the kinds of knowledge and capabilities required in an integration future, so that they can make better career choices. Lastly, we hope to support policy makers by providing them with a better understanding of the HInt paradigm and how it will influence the HCI field (and vice versa) and with a set of key terms to use when discussing challenges across particular technology domains.

2. RELATED WORK

The notion of integrating the human body with a computational machine is not new; it has been discussed not only in computer science, but also in art, philosophy, neuroscience, and science fiction. As such, integration can be discussed from multiple perspectives and related work exists in a wide variety of fields. For example, in 1843, Edgar Allan Poe proposed a man-machine mixture in his literary work. In 1920, the playwright Karel Capek presented a humanoid robot played by an actor. In the 1960s, musician Manfred Clynes and psychiatrist Nathan Kline coined the term cyborg. In 1965, Author Dan Halacy wrote an essay arguing that a cyborg was born when humans began making tools. In the 1990's, the artist Stelarc presented himself as a cyborg. In 2006, academic Donna Haraway proposed a feminist cyborg manifesto (Haraway, 2006).

In this article, we target readers who are from, or interested in, the computing field and consider relevant prior work on integration. For example, Wiener's seminal piece on cybernetics, an early work that aimed to change how we interact with computational machines, proposed closed-loop machine systems (Wiener, 1948). Similarly, Licklider proposed the design of human-computer symbiosis. Licklider depicted cooperation between users and computational machines, enabled through a "very close coupling" between the human and computational machine (Licklider, 1960). Soon after, Engelbart proposed an augmentation of human intellect (Engelbart, 1962) whereby technology amplifies a user's cognitive abilities. Clark appreciated these developments but also introduced a more critical perspective, arguing that the notion of a cyborg was not very futuristic. He pointed out that humans had integrated technology with their bodies well in advance of these stories (Clark, 2001). Clark pointed out that traditional spectacles could already been regarded as successful technology integrations with the human body (Clark, 2001). We agree with Clark that integrating technology with the human body is not exclusive to interactive digital technologies. In fact, we point to prior work on how riders can integrate with their bikes to the point where they feel like "one" with the bike (Spiegel, 2002), similar to how people wearing spectacles do not experience the world *through* the lenses but rather integrate the spectacles into their bodily experiences. In this article, we build on this by focusing on digital, interactive technologies as we believe they can enable richer and more advanced integration experiences compared to traditional non-digital technologies like the spectacles and bikes mentioned above. For example, traditional spectacles can generally only offer one particular eyesight correction and not dynamically adjust to different circumstances and user needs. In contrast, digital interactive technology can play its strength here of being able to dynamically adjust: for example, prior work has demonstrated spectacles in the form of augmented reality glasses that allow to see infrared light on command, i.e. when the user squints their eyes (Schmidt, 2017). Similarly, Andres et al. have equipped bicycles with interactive digital technology to allow an electrical engine to dynamically offer pedaling support when needed, based on both user input (Andres et al., 2018) and environmental circumstances, such as helping to reach traffic lights at the precise moment when they turn green (Andres et al., 2019). As such, we believe that digital, interactive technologies allow for new enriched and advanced ways to integrate the human body with the computational machine. Hence, we hope that our article has the potential to inform the design of future systems. Nevertheless, we believe that acknowledging that integration has already been discussed around non-digital technologies offers a historical context while potentially outlining the breadth of the technological landscape.

Rosenberger and Verbeek argued that "cyborg relations" emerge from "embodiment relations" where the human and computational machine are so tightly coupled that it is difficult to dichotomize one from the other (Rosenberger & Verbeek, 2015). This tight coupling speaks to our integration paradigm. Raisamo et al. have begun to collect systems that aim to create such tight couplings (Raisamo et al., 2019). Taken together, these prior works provide a foundation for our discussion and conceptualization and serve as a basis for our thinking.

2.1 Point of departure

Our work takes Farooq and Grudin's (Farooq & Grudin, 2016) articulation of human-computer integration as its point of departure, particularly their compelling notion of the human and computational machine working as partners. Farooq and Grudin depict a human-computer relationship that goes beyond that advocated by proponents of human augmentation (Raisamo et al., 2019), taking the relationship further than technologies like Clark's spectacles example (Clark, 2001) that enhance just one particular human sense. In order to investigate this extended relationship and the computer-as-partner role, Mueller et al. (2020) provide a conceptualized and illustrated integration as occurring at different scales, from the macro, societal level to the micro level of organs and organelles, and describes systems that exhibit a symbiotic relationship, whereby the human and computational machine work together "towards a shared goal or towards complementary goals" (Mueller, Lopes, et al., 2020). These systems speak to Mann's "Humanistic Intelligence" (2001) because they can be characterized by their continuous feedback loop, with the computational machine continuously working on the user's behalf.

We also learned from prior work on human augmentation (Alicea, 2018; Papagiannis, 2017) (Raisamo et al., 2019). Alicea argued that human augmentation systems enable symbiotic technological-biological relationships (based on Licklider (Licklider, 1960)) (Alicea, 2018). These systems are "influenced by cognitive and life-history (biological) processes such as attentional capacity, expertise, aging, and generalized plasticity" (Alicea, 2018), highlighting how understanding these systems can have far-reaching implications. However, Alicea does not tell us (yet) how to design such systems, hence our work is still needed.

In contrast, Papagiannis proposes that augmented reality is a key enabler for augmenting humans and offers a set of augmented reality categories as a way to augment humans, which the author believes will ultimately lead to an "uplift of humanity" (Papagiannis, 2017). Whereas her work very much focuses on augmented reality, our work investigates technology more broadly as we are interested in the interaction, that is, more precisely, the integration between human body and computational machine.

Raisamo et al. tried to define the term "augmented human" by proposing that associated technologies put "human action" at the "core": "These actions are supported with augmenting technologies that are related to perceiving, affecting, or cognitively processing the world and information around the user" (Raisamo et al., 2019). This resulted in the definition of human augmentation as an "interdisciplinary field that addresses methods, technologies and their applications for enhancing sensing, action and/or cognitive abilities of a human. This is achieved through sensing and actuation technologies, fusion and fission of information, and artificial intelligence (AI) methods" (Raisamo et al., 2019). This definition helps to bound the field as a whole together, which we appreciate. However, our work aims to help future work in human-computer integration. As such, our work is future-oriented and hence aims to go beyond Raisamo et al.'s more descriptive account. Furthermore, we find that human-computer integration is more narrowly focused on systems that work with the human as partners. This speaks to the aforementioned discussion by Clark who argued that simply enhancing sensing through traditional devices like glasses is already a form of augmentation. We argue that interactive technologies have become so advanced that they can go beyond and take on a partner role. However, we acknowledge that the boundary is a blurry one and difficult to articulate, especially as Raisamo et al.'s paper (Raisamo et al., 2019) also mentions Farooq and Grudin's (Farooq & Grudin, 2016) original human-computer integration article. However, this discourse appears to focus on computers that could "work in parallel with the human" and hence seems to home in on "artificial intelligence assistants" (Raisamo et al., 2019). We believe that a partnership with the user can benefit from technical advances such as machine learning and ultimately artificial intelligence but find that this might not be a requirement.

Nevertheless, we agree with Raisamo et al. that wearable technology has made significant advances recently (Raisamo et al., 2019). This is for us a key enabler to bring the field of human-computer integration forward. In particular, we are inspired by developments by the engineering and design communities that resulted in systems that have moved beyond being simply "wearable", i.e., being concerned with making computers smaller, to devices that aim to truly integrate with the human body (H.-L. C. Kao, Bedri, & Lyons, 2018), For example, we are inspired by prior work that managed to incorporate sensing with the body (H.-L. Kao, Dementyev, Paradiso, & Schmandt, 2015) and producing input and output devices directly on the human skin, for example by using gold leaf as material (H.-L. C. Kao, Holz, Roseway, Calvo, & Schmandt, 2016). Building on this, more recent works have shown that this does not have to be a manual process but can be automated or at least supported by toolkits (Buruk, Genç, Yıldırım, Onbaşlı, & Özcan, 2021), allowing to produce skin-based interfaces that are personalized and hence unique to each body more easily (Choi, Ryu, Kim, Dementyev, & Bianchi, 2020). This work has led to advances that not only integrate with the human body, but also support the development of the device itself through seeing the computer as a potential partner. For example, the work on the "BodyStylus" enables users to produce their own skin-based interfaces using a stylus, with the computer aiming to prevent any errors by correcting any small mistakes in the stylus handling (Choi et al., 2020)

In addition to these investigations that aim to integrate computing devices with the human body, we also learned from prior work that explored how such systems can act in concert with the user of such systems. We refer to examples such as developments that aim to act in concert with the user during creative tasks (Bretan & Weinberg, 2017) or during tasks that benefit from expert knowledge, with the system providing the expert knowledge in concert with the user executing their task (Lopes, Yüksel, Guimbretière, & Baudisch, 2016). Furthermore, there is prior work that explored what different applications such systems that work in concert with the user could facilitate (Dementyev et al., 2016), noting that these systems do not represent information symbolically, but rather, through embodied mediation (Mueller, Lopes, et al., 2020; Verbeek, 2005).

More broadly speaking, these prior works investigated what has previously been discussed under the term mixed-initiative interaction (Allen, Guinn, & Horvtz, 1999). Such mixed-initiative interaction investigations initially appeared to focus on screen-based mouse and keyboard interactions in which the computer could take on a more active role than simply responding to commands, instantiated mostly, at the time, through conversation-based agent systems. We build on this prior work by proposing that going beyond mouse and keyboard allows for additional and conceptually higher levels of integrations between the computer and the human (body) and investigate this opportunity in this article.

For this, we lean on prior work on mixed-initiative interactions that told us about what it means to share agency between computer and user (Bradshaw et al., 2003). For example, Bradshaw et al. proposed a set of dimensions to describe such interactions. We, similarly, use dimensions to visualize our thinking. The authors argue that we should differentiate between actions a system can perform and actions that a system is allowed to perform. This differentiation speaks to our article in so far as it highlights that an integration system might be able to support a user but should not do the work entirely "for" the user, effectively replacing the user.

At this point, we wish to emphasize the unique opportunities offered by a particular group of acting-as-partner systems as they form the central focus of our paper: "bodily integration" systems (Mueller et al., 2021) that possess specific characteristics, and, we believe, they arguably offer insights into a fascinating human-computer integration future. These individual (rather than societal level) systems achieve a fusion between the human body and the computational machine, and their devices extend the human body or the human body extends their devices. "MetaArms" represents one example of a "bodily integration" system (Saraiji, Sasaki, Kunze, Minamizawa, & Inami, 2018). Additional arms are attached to the user's back and, in situations where two arms are not enough, such as when soldering, the user can use their feet to control the arms. Another example is "Muscle-Plotter". It is a system that uses electrical muscle stimulation to control the user's hand, thereby giving them the ability to draw computation-informed simulations (Lopes et al., 2016). There are also other examples of bodily integration systems involving implanted devices (Holz, Grossman, Fitzmaurice, & Agur, 2012; Strohmeier, Honnet, & Von Cyborg, 2016), ingested devices (Zhuying Li et al., 2018), epidermal electronics (Steimle, 2016) and devices that extend or manipulate the body (Shilkrot, Huber, Meng Ee, Maes, & Nanayakkara, 2015; Svanaes & Solheim, 2016) or stimulate the senses (Seim et al., 2014; Strohmeier, Boring, & Hornbæk, 2018; Wolf & Bäder, 2015). We also point to a trend that appears to aim to go beyond mechanical contraptions (like mechanical exoskeletons) on the human body, and, instead, utilizes the human body's "softness". Amongst other things, this trend promotes soft robotic suits (Xiloyannis et al., 2021) and skin-inspired interfaces (Teyssier et al., 2019).

In summary, we see integration as an analytical lens for designing the ways in which humans and computational machines relate. We now discuss two aspects of integration by articulating them as dimensions, forming a design space of human-computer integration systems.

3. DESIGN SPACE OF INTEGRATION

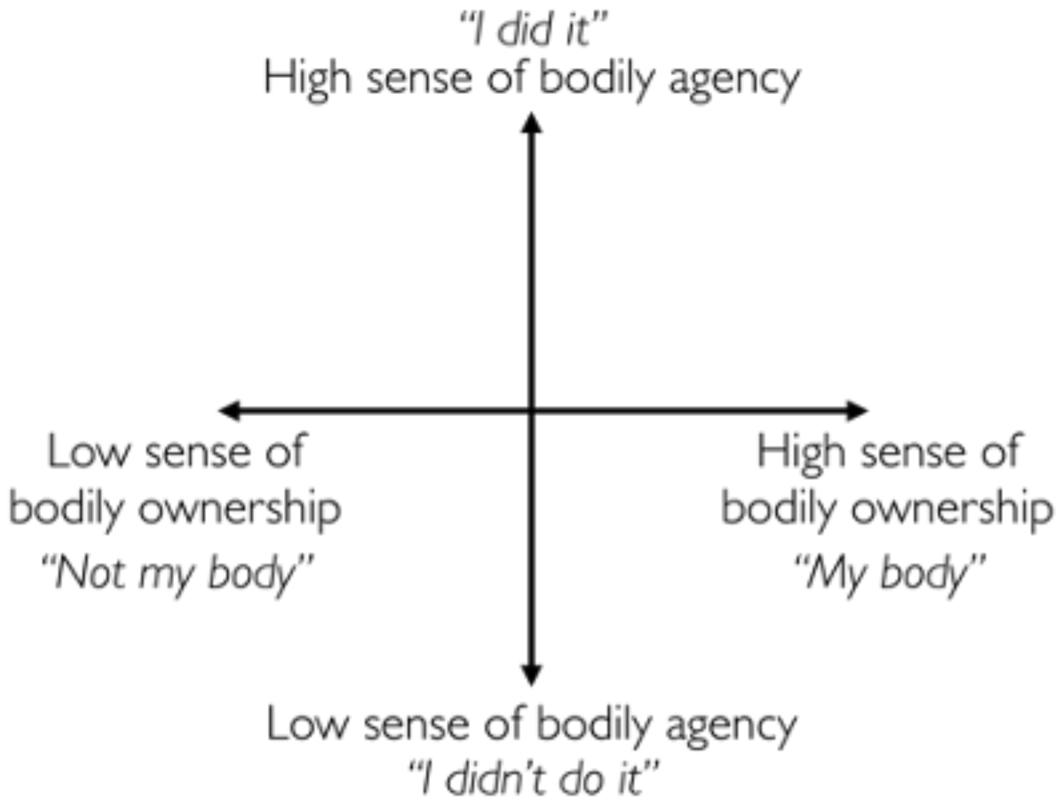

Figure 1. Two dimensions: bodily agency and bodily ownership.

Prior work highlighted two key dimensions for the design of integration between the human body and the computational machine: "bodily agency" and "bodily ownership" (Mueller et al., 2021). These dimensions refer, respectively, to the user having a sense of control over the fusion of the body and the computational machine and to the user's sense of the computational machine being a part of their body (Figure 1). Our framing of the design space along these two dimensions was informed by psychology research (Blanke & Metzinger, 2009) that argued that both agency and ownership play an important role in "any self-experience" (Braun et al., 2018). We argue that human-computer integration experiences are self-experience subsets because they concern the extension or control of the "self" through technology. Prior psychology research has also highlighted that the experiences of a sense of agency and ownership does not need to be mutually exclusive (Braun et al., 2018).

We acknowledge that these two dimensions are not necessarily the only ones that can be used to discuss the challenges facing HInt, and that additional dimensions might help identify other challenges. For example, Benford et al. consider additional dimensions, including awareness, surrender and looseness (Benford et al., 2020). Nevertheless, we believe that our dimensions offer a useful structured approach to discuss challenges, and we note that two dimensions have been successfully employed previously to discuss the related topic of embodied interactions (Mueller, Matjeka, et al., 2020).

We now articulate the bodily agency dimension of human-computer integration.

4. THE BODILY AGENCY DIMENSION

The bodily agency dimension is concerned with the degree to which the user has a sense of control over the fusion between human body and computational machine. This sense of control can be complex in nature. The user might (or might not) experience a sense of control over their body or/and experience a sense of control over the computational machine.

In psychology, the sense of agency is described as "the experience of initiating and controlling an action" (Braun et al., 2018). This sense of bodily agency is often described as a feeling of ownership: "*It must have been me who just pressed this button*" (Braun et al., 2018); and "*I did that!*" (Bergstrom-Lehtovirta, Coyle, Knibbe, & Hornbæk, 2018). This sense can be illustrated through the example of arm movement. Distinguishing self-generated actions (I am moving my arm) from actions generated by others (you are moving my arm) highlights the sense of bodily agency. If I move my arm, I am the one causing the movement. If someone else, or some computational machine, moves my arm, I still have the sense that I am moving but the movement is involuntary because someone else took control of my arm (Gallagher, 2013). As a result, I would say: "*I did not move my arm, it was you [the computational machine]!*"

Prior HCI work has already identified that a sense of agency is important to consider when designing interaction systems (Benford et al., 2020; Bergstrom-Lehtovirta et al., 2018; Coyle, Moore, Kristensson, Fletcher, & Blackwell, 2012; Kasahara, Nishida, & Lopes, 2019; Limerick, Coyle, & Moore, 2014). With advances in artificial intelligence, and especially machine learning, it appears that computational machines are increasingly able to take some control of the interaction, thereby becoming valuable partners. However, it is difficult to design for taking-over of control, and more research is needed to fully understand how control is taken, when it is taken, and the degree to which it is taken, and equally, how, when, and to what extent control is given back (Berberian, 2019). In this context, while we maintain that it is important for people interested in integrated systems to consider the sense of agency, we also recognize that there is a need for further research of this dimension.

With respect to human-computer integration, a sense of agency is primarily concerned with motor control because motor control processes are believed to be "almost always involved" in our everyday experiences (Gallagher, 2013). However, prior work points out that a sense of agency can entail aspects beyond bodily boundaries (Braun et al., 2018) and that advances in brain-computer interfaces allow for integration beyond motor control (Semertzidis et al., 2020). Consequently, we highlight that while current human-computer integration appears to focus on a sense of agency in terms of motor control, the investigation of non-motor control processes is still underdeveloped, and we suggest exploring this in future work.

Our presentation of bodily agency along a dimension, whereby users can experience something between "a lot" (high) and "a little" (low) bodily agency is based upon prior work that argued for the conceptualization of agency in this way (Benford et al., 2020). We begin by presenting the two ends of the bodily agency dimension.

4.1 A high degree of bodily agency

At the high end of the dimension, we find systems that allow the user to have a high sense of control over the fusion of their body and the computational machine. A typical example is a prosthesis, as it aims to replace an existing limb and (at least aims to) offer the same degree of control as the lost limb.

4.2 A low degree of bodily agency

On the low end of the bodily agency dimension, we find systems with which the user experiences a low degree of control over the fusion of their body and the computational machine. At first glance, it might be obvious that it is undesirable to have integration systems provide a low degree of bodily agency. However, this experience could be a result of technical limitations or be deliberately designed. For example, most current exoskeletons limit a person's degree of freedom of movement due to the mechanical contraptions that are focusing on the effectiveness of one movement, at the cost of another. While an exoskeleton might help a person lift heavy boxes from the floor, the exoskeleton's mechanical hinges could prevent turning actions. Similar, some movements could be restricted to avoid the person to perform harmful actions (e.g., poor postures).

5. THE BODILY OWNERSHIP DIMENSION

"Bodily ownership" is the other key dimension we present in this article. As with bodily agency, we argue that bodily ownership has a non-unitary phenomenal structure (Braun et al., 2018) and present it along a dimension. The bodily ownership dimension is concerned with the degree to which the user experiences a sense of ownership over the fusion between their body and the computational machine.

Braun et al. explained that a sense of ownership "describes the feeling of mineness toward one's own body parts, feelings or thoughts" (Braun et al., 2018), and they found that this feeling is what "most of the research conducted so far has focused on" (Braun et al., 2018). A sense of ownership is often expressed in statements such as "*This is 'my' hand*", with reference either to individual limbs or to the whole body (Braun et al., 2018).

Most famously, the "rubber hand illusion" (Botvinick & Cohen, 1998) demonstrated that the feeling of mineness towards one's own body is not always obvious. In the illusion, a rubber hand is positioned on a table in front of a person, as if it were their real hand. The person's real hand is placed underneath the table, out of view. The rubber hand and the person's hand are repeatedly stroked in synchrony. The result is that the person experiences a sense of ownership of the rubber hand. This sense of ownership goes as far as the person retracting their real hand in fear when the rubber hand is approached with a knife (Armel & Ramachandran, 2003; Guterstam, Petkova, & Ehrsson, 2011). These results suggest successful embodiment of the rubber hand: it becomes "mine" (Armel & Ramachandran, 2003).

Research has since built on the original rubber hand illusion and examined the roles that interactive technology can play in this type of experience. For example, Lenggenhager et al. have shown that people using Virtual Reality (VR) headsets can feel as if a virtual body in front of them is their own body (Lenggenhager, Tadi, Metzinger, & Blanke, 2007). In response, we argue that bodily ownership should be considered also during the design of integration experiences, as the mineness of the body can be affected, either deliberately or incidentally, through the fusion of the human body and computational machine.

We now present the two ends of the bodily ownership dimension.

5.1 A high degree of bodily ownership

At the high end of the dimension, we find systems with which the user experiences a high degree of mineness. Mueller et al. offer prostheses as examples, because they are meant to be worn continuously, and for long periods, and (hopefully) they seem to fuse with the human body (Mueller et al., 2021).

5.2 A low degree of bodily ownership

Systems that facilitate a low degree of mineness can be found at the other end of the dimension. These systems fuse with the human body but participants feel distinctly that they are not "theirs". Experiments have shown that VR technology can be used to alter this sense of bodily ownership (Braun et al., 2018), in both directions.

6. BODILY INTEGRATION DESIGN SPACE

We now use the two dimensions of bodily agency and bodily ownership to articulate a design space. We are then able to situate examples from the integration research field in this design space. The design space can be used to describe different user experiences as a result of integration, and we articulate these experiences by using each of the four design space quadrants (Figure 2), beginning with the "Super-Body" quadrant.

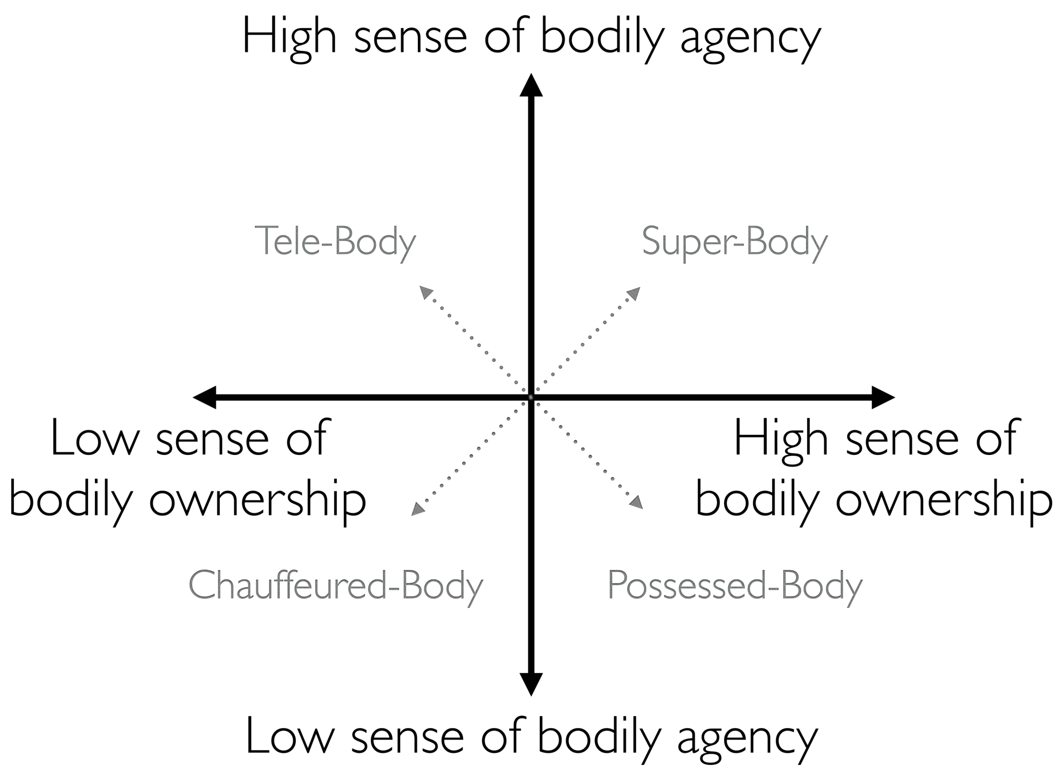

Figure 2. The four user experiences of integration.

6.1 Super-Body

The "Super-Body" quadrant encompasses systems with which the user experiences a high degree of bodily agency and bodily ownership. The user often has an experience of possessing superhero abilities.

The "Superhuman Sports" initiative (Superhuman Sports, 2020) sits in this quadrant, as it develops interactive systems for future sports competitions in which athletes experience superhuman abilities. For example, associated researchers have created leg attachments that allow athletes to jump higher (Superhuman Sports, 2018). The aim of this research is to give the athlete a high sense of bodily agency so that they can compare their prowess, and to facilitate high bodily ownership so that the athlete believes the prowess belongs to them.

Another example in this quadrant is the EMS-powered system (Kasahara et al., 2019) that allows participants to perform faster movements than they could without the system. For example, the system enables participants to more quickly catch a falling pen or take a photo of a fast-moving baseball. The use of EMS facilitates a high degree of bodily ownership among participants; they feel that it is "their" hand that catches the falling pen or presses the camera shutter.

We now articulate a future outlook for Super-Body systems and describe the key opportunities for designers aiming to develop Super-Body experiences.

6.1.1 Future outlook: Opportunity

A key opportunity for systems in this quadrant is that they allow participants to experience what it might feel like to become who they want to be. Because the systems allow people to become enhanced versions of themselves, people have the opportunity to experience what a future version of themselves feels like (Mueller & Young, 2017, 2018), allowing them to better judge whether that is actually who they would like to be. For example, a participant could experience what it might feel like to have more muscle strength, which could increase their motivation to attend more gym classes.

Another example application scenario is concerned with becoming a musician. Prior research has suggested that EMS can be used to help people learn how to play an instrument, such as the guitar (Nith, Teng, Li, Tao, & Lopes, 2021; Tamaki, Miyaki, & Rekimoto, 2011). With respect to the guitar, an EMS device could help the user move some of their fingers to the right position on the fretboard or help pressing down hard enough as part of the music-making experience. In contrast to, for example, the user controlling a robot to play the guitar, the user would probably experience a higher sense of bodily ownership as it is their fingers that move over the fretboard, not the robot's fingers. In terms of bodily agency, if the user is a beginner, the EMS will probably do most of the heavy lifting, that is, move the user's fingers like a puppeteer, resulting in the user probably experiencing a low sense of bodily agency (discussed further below, under "possessed body"). If the user is more advanced (or becomes more proficient as a result of using the system), the system might then only help the user to place their fingers more accurately or improve their timing. The result of using this system is a "Super-Body" experience in which the user has a high sense of bodily ownership and a high sense of bodily agency. The user "feels" like they are playing themselves, possibly strengthening any belief that they can be, or already are, a musician. This research builds on prior work, which highlights that a high sense of bodily ownership can be a significant contributor to the strengthening of the belief that one can be indeed a musician, which facilitates an engaging user experience (Bianchi-Berthouze, 2013).

6.2 Tele-Body

The "Tele-Body" quadrant encompasses systems that facilitate high bodily agency and low bodily ownership. This combination of high agency and low ownership reminds us of telepresence avatars or robots (Kristoffersson, Coradeschi, & Loutfi, 2013), particularly those robots that can "copy" bodily actions performed by the user. These robots are often advocated to be solutions in situations where human beings are in danger, such as polluted areas like nuclear disaster zones. The human operator is equipped with sensors so that an action is replicated by the robot in the remote (dangerous) area, while the operator receives haptic feedback through sensors on the remote robot. The "telexistence cockpit for humanoid robot control" (Tachi et al., 2003) is one example of such a robot. We call systems in this quadrant of the design space "Tele-Body" because the user appears to have a remotely operated, "mirrored" body.

Tele-Body systems aim to facilitate a high degree of bodily agency as they mostly try to replicate the user's bodily actions one-to-one to the robot's body. We can contrast this high bodily agency with a remote robot that would execute most actions autonomously, for example a robot that receives only the command "collect evidence" and would then go about executing the task on its own, eventually returning with the evidence.

On the other hand, due to the existence of the second "mirror" body, there is a relatively low degree of bodily ownership.

We note that "Tele-Body" systems can take on various forms. These forms can affect the experience, for example, prior research has aimed to create humanoid forms (Nishio, Ishiguro, & Hagita, 2007) as a way to positively inform the "Tele-Body" experience (Kawaguchi, Kodama, Kuzuoka, Otsuki, & Suzuki, 2016; Sakamoto, Kanda, Ono, Ishiguro, &

Hagita, 2007). Another example is the "telexistence cockpit for humanoid robot control" that has been designed to replicate a human form in order to operate in remote areas inaccessible to humans (Tachi et al., 2003). Research around the physical form of "Tele-Body" systems highlight that the user experience can vary, both for the user of the system on the remote end but also others interacting with the system locally (Lee & Takayama, 2011), even affecting agency (L. Takayama, 2015). For example, research has investigated how to share agency between a "Tele-Body" system that has two arms that aim to replicate the two arms of the user (Rakita, Mutlu, Gleicher, & Hiatt, 2019); we are wondering how this agency needs to be designed if the two arms are controlled by the user's feet (as hinted at by Saraiji et al. (Saraiji et al., 2018)) or what if the "Tele-Body" system has three arms or the user only one?

Prior work has used such different forms of "Tele-Body" systems to explore different social (Nishio et al., 2007) and physical capabilities (Rakita et al., 2019) and we believe there is interesting future work to be done in order to further unpack our understanding of the "Tele-Body" quadrant. In particular, we find alternative forms such as drone systems interesting emerging forms of "Tele-Body" systems. The Tele-Body experience is facilitated through the quadcopter camera, which provides a first-person view of a remote place, especially when the operator wears first-person view goggles (a high degree of bodily agency). We would argue that the drone operator experiences a low degree of bodily ownership as they generally do not consider the drone a part of their body. Rather than their body "being part of" the drone, they experience themselves looking "through" the drone at a remote place. However, the drone operator can explore a remote space not just from an eye-level, but also through flying, enabling a "Tele-Body" experience where they gain "wings". Furthermore, their "Tele-Body" is much smaller than their own, allowing remote bystanders to only sense if a remote person is part of the space to a limited extent, enabling more covert operations, which could be beneficial but also privacy endangering. The extent of bodily ownership is probably very different in comparison to the humanoid robots mentioned above, we argue. As such, we highlight that the "Tele-Body" quadrant is an interesting part of the design space where current technical advances allow for very diverse forms to be investigated, and we encourage future work in this area.

6.2.1 Future outlook: Opportunity

One key opportunity for systems in this quadrant is that they allow users to be in more than one location simultaneously. For example, the drone operator above could easily switch between multiple drones, viewing different locations through multiple cameras (and even from several camera angles). It has been suggested that one underexplored and potentially interesting Tele-Body area could involve facilitating not just the experience of multiple locations, but also the experience of remote locations at multiple points over time (Sheridan & Mueller, 2010).

6.3 Chauffeured-Body

Systems situated in the lower-left quadrant of the design space are characterized by a low degree of bodily agency and ownership. The associated user experience reminds us of a chauffeur "driving" the human body, where there is an external force that the user experiences on their body that results in movement. We hence call this quadrant "Chauffeured-Body".

An example of such a Chauffeured-Body user experience can be seen in the "Inferno" performance (Diitalarti, 2016; Meta.Morf, 2018). "Inferno" is an arts event in which a group of volunteers stand in a dance club-like space and put on individual exoskeletons. The exoskeletons are controlled by the choreographer, who "performs" the movements of the volunteers. In this situation, we infer that the exoskeleton wearers experience a low degree of bodily agency. We also infer that their sense of bodily ownership is low, primarily because the artistic presentation highlights that the choreographer is connected to highly visible cables plugged into oversized actuators attached to the exoskeleton-wearer's upper bodies. As such, the participants experience an external force on their body (through the receptors on their skin that sense the exoskeleton's components pushing against their body), similar to as if the choreographer would step next to them and physically move their bodies using the choreographer's own hands; here, this is mediated through the exoskeleton, where the participant has a very low agency over the movements of their arms, as it is the choreographer who determines how the participant's arms move.

6.3.1 Future outlook: Opportunity

A key opportunity for systems in this quadrant is to facilitate experiences that promote "letting go" as a welcomed bodily sensation. The underexplored potential of interactive technology to facilitate this experience of "letting go" has been highlighted previously (Leong, Howard, & Vetere, 2008) and we point to the opportunity to facilitate such experiences at a bodily level to produce unique bodily sensations.

6.4 Possessed-Body

Systems situated in the lower-right quadrant of the design space are characterized by a low degree of bodily agency and a high degree of bodily ownership, resulting in a user experience that can be described as the user's body being internally "possessed" by an external entity (in contrast to the "Chauffeured Body", where an outside force acts externally on the user's body).

EMS provides a typical example of technology that often results in such possessed user experiences. Normally, EMS users are aware that while they are not authoring the actuated movements (low extend of bodily agency), the movements are certainly executed by their body (high degree of bodily ownership). For example, Pfeiffer et al. (2015) demonstrated an EMS system through which the computer can confer walking directions by stimulating the user's thighs to rotate their legs. In this case, the user experiences a high degree of bodily ownership over their leg (it is, after all, "their" leg), but they do not initiate the rotation of their leg: the leg seems to rotate "on their own".

Another Possessed-Body example is an artwork that uses EMS to control facial muscles through digital sounds (Manabe, 2008). In this case, the user's face moves seemingly without the influence of any external force (high degree of bodily ownership), but the movements are controlled by sounds (low degree of bodily agency).

A third Possessed-Body example is an EMS system (Lopes, Jonell, & Baudisch, 2015) that "demonstrates" to users how to interact with new objects by moving their body, causing them to directly manipulate the object while using the correct poses. The work intends not to convince the user that they are causing the action, but to give an embodied instruction of the required action. An alternative implementation of the system could use a robot that would "chauffeur" the user's hand so that the user would interact with the objects in the right way; this implementation would be in the "Chauffeured-Body" quadrant, as the user sees as well as experiences through their receptors on their skin that an external force is aiming to move their body.

While these examples suggest the potential for EMS-based systems to contribute to the Possessed-Body quadrant, we also point out that users have described the experience of an EMS system controlling their limbs as "scary", being "pushed by someone", or being "hacked" (Mueller, Kari, et al., 2020; Tamaki et al., 2011). It feels as if the user's own body (high degree of bodily ownership) is not controlled by them, but internally "taken over" (low degree of bodily agency). Strangely, in this instance it is not an external entity that acts on the user's body, but the user's body seemingly acts on itself. This peculiar and uncanny description might appear unfamiliar and certainly does not occur often in everyday life for most people.

6.4.1 Future outlook: Opportunity

A key opportunity for systems in this quadrant is to help users outsource mundane or unengaging tasks. For example, a user might need to stamp several letters and could use an EMS system to execute the stamping task. This could reduce cognitive load, allowing the user to focus on another task with their other hand. Unlike outsourcing the task to a robot, the difference here would be that the user still believes the task execution to be theirs, which might be seen as important, for example, when undertaking an approval process.

7. CHALLENGES

We now articulate a set of challenges that we believe that the HInt paradigm is facing and that need addressing. We believe that by articulating these challenges, we can inform future research in the area, allowing the HInt paradigm to fully unfold its potential in a way that is beneficial for humankind. Furthermore, we hope that through articulating the challenges along with suggestions on how to address them, we give hope that these challenges can be overcome. As such, we paint a positive picture of the future, which we acknowledge reflects our personal belief. Other, more dystopian views will therefore complement our work.

In addition, we believe that the approach of articulating challenges can be useful, as we have seen it applied in other technology fields, such as applied to social robotics (Tapus, Mataric, & Scassellati, 2007), crowdwork (Kittur et al., 2013), information retrieval (Belkin, 2008), shape-changing interfaces (Alexander et al., 2018), data physicalization (Jansen et al., 2015), cross-device interactions (Houben et al., 2017) and immersive analytics (Ens et al., 2021). It appears that identifying and formalizing challenges for emerging fields is increasingly common and hence might suggest usefulness for other researchers. However, of course, we acknowledge that there are also discussions around their usefulness (Beck & Stolterman, 2017).

Our challenges build on prior work on "next steps" (Mueller, Lopes, et al., 2020) for integration research that were based on a Dagstuhl seminar, a week-long workshop with experts (Grudin, Höök, Maes, & Mueller, 2018). This seminar charted an agenda for next steps and also identified challenges. We group the challenges and identify those we believe are of "high importance". We interpret "high importance" challenges as those that are fundamental to HInt's development.

We propose four categories of challenges, design, society, identity, and technology (Mueller, Lopes, et al., 2020). We believe these categorizations reflect the cross-disciplinary nature of HInt. We did not put the categorizations in a particular order as a prioritization did not seem to be readily apparent. Furthermore, we acknowledge that isolating these categorizations is also challenging, as they are often interconnected, which again makes prioritization more complex. Nevertheless, we believe that our categorization is a useful start, and we encourage others to identify further categorizations and additional challenges.

We summarize the challenges in the table below (Table 1).

Challenge	*Sub-challenges*
Design	Designing body-conforming material to support bodily ownership
	Designing implicit interactions that consider bodily agency
	Designing visceral responses to reduced bodily agency
	Designing variable bodily agency
	Designing perceptual transparency for bodily ownership
	Designing perceptual transparency to understanding others' bodily ownership

Integration and society	Technology gap amplified through bodily ownership
	Designing accessible systems with bodily ownership
	Designing for health in response to altered bodily agency
	Designing for accountability in response to altered bodily ownership
Effects of integration on identity	Affecting self-concept through multiple modalities facilitated through altering bodily agency and bodily ownership
	Affecting other's self-concept via altered bodily agency and bodily ownership
	Evaluating self-concepts as a result of altered bodily agency and bodily ownership
Body-compatible technology	Key types of body-compatible technologies in relation to bodily agency and bodily ownership
	Materials for integration for altered bodily agency and bodily ownership

Table 1. A set of challenges HInt is facing.

7.1 Challenge #1: design

This section is concerned with the challenges interaction designers face when designing human-computer integration systems. We use the aforementioned dimensions, bodily agency and bodily ownership, as a way to articulate the challenges across the following headings.

7.1.1 Designing body-conforming material to support bodily ownership

We believe that in order to support bodily ownership, it can be advantageous if the material of the HInt system can conform to the human body. However, most existing technology falls short in conforming to the human body due to its rigid form factor, and hence developments have been underway to create more body-conforming materials. Here, we point out that solely creating these new technologies is not necessarily sufficient to make them suitable for design practice. Interaction designers do not just need to be exposed to these materials, they also need affordable and accessible toolkits that allow them to experiment with the materials as part of their creative practice. A "material turn" has already been identified in HCI, highlighting the value of material characteristics to people's experiences with technology (Wiberg, 2018). Building on this work, we contend that new materials that can conform to the human body for integration will probably only find their way into system design if they come with hardware toolkits and software APIs that allow interaction designers to integrate them straightforwardly into their creative practice. For example, although it is increasingly possible to 3D-print soft material that can lend itself to attachment to the human body, easy-to-use toolkits that make experimenting around the human body straightforward are still rare.

7.1.2 Designing implicit interactions that consider bodily agency

Prior work has proposed that integration design could benefit from looking at other non-digital, tightly-coupled partner experiences, like ballroom dancing (Höök, 2010). The interactions associated with these experiences can be characterized by their implicitness, where the partners operate just beneath or just above the user's awareness as well as just ahead or just behind the user's intent. However, how to design such implicit interactions is still an open area of research (Ju, 2015), with very little work done with respect to the exploration of implicit interactions and computational machines integrated with the human body. For example, contrast a dance partner who aggressively pulls the other dancer around the floor with a partner who subtly guides the other dancer towards the right movement. Furthermore, we point out that most implicit interactions can be characterized by their fast speed, so designing for them has to be concerned with not only how to sense such implicit actions and how to manage the change in agency, but also how to do all this at the right speed and preferably in real-time.

7.1.3 Designing visceral responses to reduced bodily agency

Designers of systems with reduced bodily agency should take note that users can experience quite strong visceral responses. A limited sense of bodily agency can, like a rollercoaster, lead to motion sickness and similar sensations of unease, although fairground rides are generally of short duration, which reduces the motion sickness risk. Designers should either try to reduce such visceral responses or frame them in the right context, such as offering users a kind of experiential exchange, as is the case with some fairground rides: visceral responses are exchanged for a thrilling experience. In this regard, it is important that designers consider how long users are exposed to reduced bodily agency.

7.1.4 Designing variable bodily agency

We argue that successful integration systems often do not have bodily agency as a fixed parameter, but rather allow agency to vary during use. The result is a user experience that moves across the design space. This variable agency allows users to feel in control at the same time as it enables them to give away control when it is not needed or when other tasks require their attention.

Given that we are only just beginning to understand how to design for agency (Braun et al., 2018; Moore, 2016), knowledge about how to design for *variable* bodily agency remains very limited. Open questions include, for example, how to sense when users are getting uncomfortable with reduced agency; how to design the return of agency in an appropriate way that does not result in surprise; and how to help users understand that they can regain any lost agency at any point in time.

While methods from other disciplines, such as intentional binding (Bergstrom-Lehtovirta et al., 2018; Coyle et al., 2012), might help with the development of our understanding, how to apply these methods to design practice remains an open challenge, especially given that emerging technologies, such as EMS, allow for new understandings of agency (Kasahara et al., 2019). Therefore, it is imperative that designers are supported with knowledge on how to design for variable bodily agency when aiming to create integration systems.

7.1.5 Designing perceptual transparency for bodily ownership

Perceptual transparency has been described as the direct transfer of sensations between a user and a computational machine (Mueller, Lopes, et al., 2020). This is achieved through embodied mediation (Verbeek, 2005), whereby the user can “directly” perceive the desired sensation. This approach is often contrasted with a hermeneutic approach, whereby information goes through an interpretative step (Verbeek, 2005). For example, systems might allow users to perceive temperature “directly” through heating pads attached to the human body, such as in “HeatCraft” (Zhuying Li et al., 2019). In contrast, a mobile phone weather app usually represents temperature through a number that users cross-reference with their lived experiences to infer what the outside temperature might feel like. This can be described as an interpretive, non-direct way of engaging with information, whereas integration systems usually engage embodied mediation that allow for a more direct way to reflect on one’s current state of being.

Engaging with perceptual transparency is probably most evident in VR applications, where head-up displays transport users to other places through visual cues. These features are now increasingly supplemented by the provision of additional information that provides users with artificial sensory experiences, such as the experience of texture where there is none (Romano & Kuchenbecker, 2011), sensations of resistance and weight (Strohmeier et al., 2018) or phantom touches (Muthukumarana, Elvitigala, Forero Cortes, Matthies, &

Nanayakkara, 2020). While these systems demonstrate the potential for perceptual transparency through sensory access, they are mostly limited to one particular sense and are often location specific. This is important for bodily ownership, as we believe that if a haptic glove only provides sensory access on the fingertips, but not on the fingers themselves, nor on the palm of the hand, and so on, the potential for the user to experience the virtual hand as their own will be smaller, when compared to a glove that offers haptic feedback all across the hand.

7.1.6 Designing perceptual transparency to understanding others' bodily ownership

Perceptual transparency is not just concerned with sensory access for the user's body. Because we are social beings and understand others through our shared experience of having a body, perceptual transparency is also concerned with an understanding of others. This quality speaks to bodily ownership as it helps users to understand where their body begins, and the bodies of others end.

With respect to bodily ownership, we have not yet discussed people having an embodied understanding of others through their shared experience of having a body. For example, while people assume their own movements to be equivalent to the movements of others (Carman, 1999), they can in fact be very different. Sheep dog and shepherd interactions offer one example of participants who have very different sensorial perceptions but can, at the same time, participate in a highly collaborative experience. In the same vein, we argue that integration systems should also be able to consider other's mental states, goals and motivations (Mottelson & Hornbæk, 2016) in order to support social collaboration. However, being able to sense these things and provide information and responses to the user in a meaningful way is not a trivial challenge. The challenge of designing perceptual transparency is especially significant when it comes to supporting collaboration in a situation where one user has experience with a particular integration system but the other does not (or they might have experience with a different system), which can mean that the second user does not have an embodied understanding of the first user's altered sense of bodily ownership when using that system.

7.2 Challenge #2: Integration and society

We believe that along with the huge potential of integration systems comes a similarly large responsibility for their designers to act in an ethical way. To guide this work, we now present a set of challenges that we believe need to be addressed so that integration systems affect society in a positive way. We point out that these challenges are not a domain exclusive to academics. Industry and regulatory bodies will also need to be involved to address these challenges.

7.2.1 Technology gap amplified through bodily ownership

If integration systems become more popular, there is potential for issues to arise because not all people have one. While such a technology gap is not specific to integration systems, we highlight that the unique characteristic of integration can potentially amplify this gap: Integration systems that facilitate a high degree of bodily ownership are perceived as being part of the user's body and, as such, others might not only look at these users with envy, but the users with the enhanced capability might forget that they only have the enhanced capability thanks to the integration system and lose their capacity to understand how others do not have these capabilities. To offer a less consequential example, when somebody asks us for directions, we might wonder why they do not simply look up the answer on their mobile phone. However, should we forget our phone one day, we might be reminded what it feels like to become lost without access to that technology.

7.2.2 Designing accessible systems with bodily ownership

Integration systems, due to their body-centric nature, can influence people to give increased attention to the human body. With this comes the challenge to design accessible systems that consider all body types, sizes and shapes while retaining the extent of bodily ownership for their users. Contemporary research has already highlighted how some biosensors function differently on skins of different ethnicities (Vinik et al., 2016), suggesting that computational machines that integrate with the human body have the potential to pose additional challenges to accessibility and universal design. For example, designers might be inclined to create devices that suit "most" bodies as a way to optimize production speed and cost. However, the result is marginalizing people with body shapes and sizes that sit outside an "average". This is particularly problematic, since technologies are – in contrast to other mass produced goods such as clothing – more difficult or impossible to adapt by the user or a local tailor after purchasing. Furthermore, accessibility can be challenged if integration systems are designed in one particular culture and then exported to another culture that has a very different understanding of the body and how to engage with it.

7.2.3 Designing for health in response to altered bodily agency

If integration systems make the human body more central to the design process, as suggested above and informed by prior work (Mueller et al., 2018), it is important to point out that this change can have implications for physical health and mental wellbeing. Interactive systems such as the desktop computer and keyboard have already led to many health issues, including bad posture and repetitive strain injury. Similarly, designers need to be aware that integration systems can have negative effects on our bodies. We point to one issue that relates to a systems' potential for changing a user's perceived bodily agency. If a user perceives that a computational machine takes control over their body, they may wish to, at least partially, outsource agency over their health to the computational machine.

7.2.4 Designing for accountability in response to altered bodily ownership

When interactive technology becomes a part of everyday life, the associated systems are not isolated devices. They are situated in a complex web, wherein the developers follow certain goals, the distributing companies want to achieve certain profits, governments use them for their intentions, regulators aim to have a say, and users want to achieve certain objectives. The intentions, goals and objectives of the different interest groups might not always align, and in extreme cases they might clash. Social network services are a typical case in point where the different objectives of users, advertising companies and regulators have clashed and resulted in much controversy.

Similar complex webs will exist for integration systems. Indeed, the associated challenges could even be amplified due to the altered bodily ownership these devices enable. By changing the degree of bodily ownership, questions around who ultimately is responsible for actions become more complex. Systems that exhibit a low degree of bodily agency and a high degree of bodily ownership will face this challenge, as the users of such systems can feel "possessed" because the computational machine appears to have taken control over their bodies. These potentials can lead to situations in which systems take a "dark turn" (Greenberg, Boring, Vermeulen, & Dostal, 2014). For example, if an EMS system harms a human being, who is responsible: is it the user, or the designer of the system? What if the user argues that, at the time of the incident, they did not experience any agency, and they deny that they had control over the system? Further questions arise if devices are permanently integrated with the human body. For example, when a company stops supporting an implant, rendering it obsolete, who is responsible for removing the implant from the user's body?

7.3 Challenge #3: Effects of integration on identity

We now discuss challenges relating to the effect that integration can have on people's perception of identity, specifically with respect to the dimension of agency and ownership. An integrated system can facilitate a varied sense of bodily agency and bodily ownership (change people's perception of whether they "did something" with "their body" or not) and these changes can alter how people perceive themselves. We contend that changes in self-perception, whether they are positive or negative, need to be carefully considered by designers. Seeing oneself differently after using a particular technology can inform later decisions and influence who a person wants to become. In this regard, we believe that integration systems have the potential to help people identify who they are, who they want to become, and how to get there (Mueller & Young, 2017, 2018).

7.3.1 Affecting self-concept through multiple modalities facilitated through altering bodily agency and bodily ownership

A person's feelings and beliefs about themselves form their self-concept (Andersen & Chen, 2002) and these feelings and beliefs are shaped by information the person obtains from different sources and modalities. Most prior work has focused on providing information through the visual and auditory senses, as a way of changing a person's self-concept. For example, experiments showed that we can change a person's body schema simply by showing them a different body than their own through a head-up display (Nishida et al., 2019; Riva, Bacchetta, Baruffi, & Molinari, 2001).

We believe that integrated systems have greater potential to shape an individual's self-concept using additional sources and modalities because they operate at a physical level and involve other senses, such as proprioception (the sense concerned with limb movements in relation to other limbs) and the kinesthetic sense (the sense of motion), not just the visual and the auditory. We specifically highlight that changing people's perception of what their body consists of, and possibly changing this perception dynamically, could change how people see their bodies and what they would like their body to look like.

Furthermore, designers must consider that systems with a high degree of bodily agency and bodily ownership carry the risk that users will become unsure how to deal with a loss of habituated bodily capacity. For example, a person could become so habituated to their enhanced ability that they will no longer feel like themselves if the manufacturer turns off support for the system.

We believe that the potential for integrated systems to affect people's self-concept and, consequently, change how people engage with themselves in regards to activities such as self-optimization – made prominent with respect to the quantified-self (Lupton, 2016; Neff & Nafus, 2016) – is an underexplored area that deserves careful investigation.

7.3.2 Affecting other's self-concept via altered bodily agency and bodily ownership

Another challenge concerns the potential of integrated systems affecting other people's self-concept via altered bodily agency and bodily ownership as the aforementioned changes to a person's self-concept do not occur in isolation: they take place within a social context. In this context, because integrated systems have the potential to extend a person's capability, it is important to consider how this extended capability affects the person's social environment. For example, if an integrated system might enable a person to react faster to moving objects than they could without the system (such as previously proposed (Kasahara et al., 2019)). Members of the person's social group can see that person's enhanced ability as positive because it ultimately improves the group. For example, the person's enhanced ability might make the group safer when facing external threats. Here, the integrated system is positively perceived based on the relationship that the person has with the group because the attribute (improving safety) has a high social acceptance in a group that values safety. We base these contentions on prior work, which argues that social groups are built around individuals to which they belong to various extents and based on a relationship between attributes, expectations and rules on which the group agrees (Tajfel, 1974). As such, the integrated system can be seen as providing the user with a high social acceptance, promoting them to a leadership position (Cuddy, Fiske, & Glick, 2008). However, others who are not part of the social group, such as a competitor in a sports event, will see the enhanced ability as providing an unfair advantage, arousing envy and even generating mistrust.

Prior work highlights that design influences a system's social acceptance. For example, making an enhanced capability more transparent can improve acceptability (Koelle, Wolf, & Boll, 2018). Furthermore, prior work has identified the importance of considering whether a technology enables a completely new capability or provides common capabilities already possessed by others. For example, it has been shown that the social acceptability of systems that help visually impaired people is higher than cameras that help people who have no visual impairment (Koelle, Kranz, & Möller, 2015).

7.3.3 Evaluating self-concepts as a result of altered bodily agency and bodily ownership

To design better integration systems, it is imperative to evaluate the user experiences of altered bodily agency and bodily ownership and changes in self-concept. Unfortunately, there is limited knowledge about how to conduct such evaluations. Prior work has examined both quantitative and qualitative ways. For example, prior work has modified existing questionnaires (Profita, Albaghli, Findlater, Jaeger, & Kane, 2016), however, they so far focus mostly on specific application scenarios rather than generic integration experiences.

Qualitative approaches have gained increased attention, particularly methods such as the explicitation interview technique (Maurel, 2009) seem to be gaining traction for evaluating integration experiences. We believe that this technique's focus on first-person accounts could help better understand integration experiences. The interviewer asks questions in a way that support interviewees in expressing their experiences linked to a specific moment. They might, for example, ask an interviewee to: "Please describe what you feel, see, hear, or perceive" in order to place the interviewee into an evocative state and encourage them to talk about a specific lived experience in a manner that includes action, sensory perception, thoughts, and emotions in detail, rather than focusing on conceptual, imaginary, and symbolic verbalizations such as theories (Mueller, Lopes, et al., 2020).

7.4 Challenge #4: Body-compatible technology

A key challenge for the future of integration systems is the development of body-compatible technology, by which we mean technology that seamlessly integrates with the human body. This challenge goes beyond the mere physical aspects of body-compatible technology; it involves the ability to collect and interpret data from the human body so that the device has a more complete picture of the user's current state. Wearables currently only sense limited data from limited sources, and biochemical and electrophysiological signals sensed by wearables to infer a user's health and fitness are still in their infancy (Imani et al., 2016). We believe that access to a richer picture of the user's state means that we will be better informed about how and when to alter bodily agency and bodily ownership. Consequently, designers should see body-compatible technology as an enabler of the ability to facilitate changes to bodily agency and bodily ownership.

We also believe that integrating technology with the human body will benefit from developments that move us beyond the rigid form factor exhibited by most current technologies. The emergence of flexible and stretchable electronics suggests a potential to design integration systems that facilitate a stronger sense of bodily ownership. Furthermore, the acknowledgement that human bodies come in all shapes and sizes, and that technology that can be personalized and customized, will be beneficial for the advancement of systems that aim to alter bodily ownership. We also contend that we need to look beyond instrumental perspectives and provide systems that users can tailor to their preferences for self-expression, because these systems can affect bodily ownership from an aesthetic perspective. Lastly, we note that there are significant challenges associated with powering body-compatible technologies, maintaining them, and connecting them to their surroundings. In the following subsections, we therefore discuss specific challenges of body-compatible technology.

7.4.1 Key types of body-compatible technologies in relation to bodily agency and bodily ownership

We identified six types of body-compatible technologies. We categorize them as they go "deeper" into the body, although some of them could work across multiple layers.

7.4.1.1 Wearable technologies

Wearable technologies have been discussed extensively in the HCI literature (for examples see (Mann, 2001; Sazonov, 2020; Starner, 2001)), here we investigate them in relation to their potential for integration experiences. In particular, we highlight that technological advances have resulted in wearable technologies that can not only sense, but also actuate the human body. Exoskeletons that sense a movement intention and then offer assistance to that movement in response are a typical example here, enabling support experiences such as allowing workers to lift heavy objects with ease, reducing any associated risk to their health (for example, see (Auxivo, 2021; "Exoskeleton report," 2017; Herr, 2009)). By sensing that a user is about to move a limb, the system usually supports a high sense of bodily agency as it is the user who authors the movement. However, the exoskeleton could also be controlled by other means, outside the control of the user, as the artistic performance Inferno suggests (Diitalarti, 2016; Meta.Morf, 2018). To what extent such systems can facilitate bodily ownership depends very much on their design, we find. In particular, we are intrigued by recent advances in soft exoskeleton research (Xiloyannis et al., 2021) that aims to create user experiences where the user feels less of being controlled by a large external mechanical contraption but rather feels like wearing a piece of clothing that functions as exoskeleton. As part of this trend, we see many opportunities for making such clothing even smaller and moving the technology even closer to the human body, resulting in epidermal technologies that are so thin that they can be worn directly on the skin, therefore affecting bodily ownership, which we discuss next.

7.4.1.2 Epidermal technologies

Epidermal technologies are worn on the skin. Unlike wearable devices, they have a thin and stretchable form factor that integrates with the skin. They are also easily applied and removed, similar to cell tape attached to the skin. We believe that epidermal technologies can easily affect the sense of bodily ownership because they are highly visible. They offer novel bodily interaction techniques, such as on-body input (H.-L. C. Kao et al., 2016; Lo, Lee, Wong, Bui, & Paulos, 2016; Nittala, Withana, Pourjafarian, & Steimle, 2018; Weigel et al., 2015; Weigel, Nittala, Olwal, & Steimle, 2017), on-body NFC (H.-L. C. Kao et al., 2016), visual displays (H.-L. C. Kao et al., 2016; Weigel et al., 2017) and haptic output (Withana, Groeger, & Steimle, 2018; Wolf & Bäder, 2015). We believe that these technologies could straightforwardly enable users to engage with bodily ownership because they are accessible from the outside of the body.

7.4.1.3 Subdermal technologies

Subdermal technologies operate in the dermis, a deeper layer of the skin, allowing access to richer biodata such as interstitial fluids. Prior HCI work investigated the extent to which common HCI input and output devices can work as subdermal technologies. For example, Holz et al. implanted LEDs, touch sensors, vibration motors and a microphone in a corpse to see if they would still function (Holz et al., 2012). Cyborg enthusiasts also implant NFC chips, and the like, into their bodies as a way to investigate a cyborg future ("Dangerous Things," ; Heffernan, Vetere, & Chang, 2016). As these devices sit under the skin, are more permanent, and can sense data from inside the body, they could be considered to support a higher degree of bodily ownership when compared to epidermal technologies. While subdermal technology can also be sensed outside the skin, our experience shows that it is a fiddly process when people try to access their NFC chips through the skin.

7.4.1.4 Transdermal technologies

Transdermal technologies contain an epidermal and a subdermal component and can therefore be considered akin to a piercing, which is an old cultural practice. They combine the advantages of the previous two technologies: allowing for a physically deep integration and access to data from further inside the body, at the same time as they allow for access from outside the body (for example to replace a dead battery). As such, transdermal technologies seem to support bodily agency well because users can control them from outside their bodies. They also seem to support bodily ownership because they can be considered a “part of the body”. We also point to the common risk of infections when using transdermal technologies.

7.4.1.5 Implanted technologies

Implanted technologies are located permanently inside the body, similar to a pacemaker, and they allow a degree of access to the body that traditional devices cannot usually offer. One of the limitations of implanted technologies is that they require surgery to install and are difficult to replace. Prior work has begun to speculate on how users might wish to interact with such devices, building on the expectation that, although existing pacemakers are not meant to be interacted with directly, future deep implanted technologies might offer this capability (Homewood & Heyer, 2017). As such, implanted technologies appear to lend themselves to a high degree of bodily ownership because they can be considered a “part of the body”, although they only support limited agency because users do not (currently) have much control over them.

7.4.1.6 Pass-through technologies

Pass-through technologies enter the body only for a limited duration. They are usually swallowed and then excreted. They often come in the form of smart pills that contain a battery and sensors that transmit data from inside the body to the outside. For example, the CorTemp sensor transmits firefighters’ and athletes’ inner body temperatures wirelessly to the outside world to help them monitor that their bodies do not get too hot (McCaffrey, Chevalerias, O'Mathuna, & Twomey, 2008). Another pass-through example is the PillCam. PillCam wirelessly transmits a video feed from a person’s colon to medical practitioners so they can conduct an endoscopy in a more comfortable way than the traditional tube insertion (Zhaoshen Li et al., 2014). These devices are excreted after approximately 24-36 hours, and prior HCI work has examined how agency over the excretion time (people could drink coffee, or similar, to speed things up) could be used as an engaging game element (Zhuying Li et al., 2018). Pass-through technologies appear to support bodily ownership as participants in associated studies described the experiences with exclamations such as “the interface was me!” (Zhuying Li et al., 2018).

7.4.2 Materials for integration for altered bodily agency and bodily ownership

We believe that technologies that consist of materials that “behave and feel” (Mueller, Lopes, et al., 2020) like the human body can be beneficial for designers aiming to facilitate an integration with the human body. We argue below that addressing challenges around the material characteristics of biocompatibility, miniaturization and deformability are important to support bodily agency and bodily ownership in integration design.

7.4.2.1 Biocompatibility for bodily ownership

Because of their close physical proximity to the human body, biocompatibility is very important for HInt devices to avoid harm to the person. The type of technology employed, as discussed above, implies the degree of biocompatibility that is required. For example, an epidermal device needs to be only biocompatible with the skin (Weigel et al., 2015), while an implanted technology (Holz et al., 2012) or a pass-through technology (Zhuying Li et al., 2018) must be far more biocompatible. Powering such devices has traditionally required batteries and, because batteries contain hazardous substances, they need to be sealed securely so that they do not break under mechanical or chemical stress. We believe that biocompatibility is important for facilitating bodily ownership because it is less likely that devices that pose significant risks to the body will be considered as a part of the user's body. Recent research results have shown that such devices can be powered from outside the body, through induction (Fan et al., 2020), while other research projects have suggested that we build superconductors made out of digestible material (Kim et al., 2017). We believe that this research provides interesting avenues for the investigation of how better integration device biocompatibility can support bodily ownership.

7.4.2.2 Miniaturization for bodily ownership

We believe that most devices are still too large to successfully integrate with humans. Even though miniaturization of the computational machine has come a long way since early mainframe computers, we contend that further miniaturization is a key challenge. Further miniaturization will particularly support bodily ownership because users are more likely to regard smaller devices as a part of their body, especially when compared to larger devices that users simply carry; such as the "Inferno" exoskeletons (Diitalarti, 2016; Meta.Morf, 2018) that were clearly not designed with miniaturization in mind.

Recent engineering feats have shown that touch sensors can be thin (4–46um) to allow for the use of small body landmarks (Weigel et al., 2017), to enable the use of the body's geometry for input (Weigel et al., 2017), and the recall of virtual elements (Bergstrom-Lehtovirta, Boring, & Hornbæk, 2017). However, the miniaturization of sensors is only one part of the challenge, processing units, batteries, actuators, antennas, etc. also need to become smaller.

7.4.2.3 Deformability for bodily ownership

To facilitate bodily ownership, devices should be deformable so that they can integrate with the body not just when it takes one particular position, but also when the human is in motion, constantly changing its pose, and therefore varying its surface, angles, and proportions. We believe that flexible, pliable and stretchable devices that can closely adapt to such a "changing" body, lend themselves to facilitating bodily ownership. We also highlight that a key challenge is to develop devices that can absorb shocks and avoid damage while, at the same time, fitting closely to the curves of the human body.

7.4.2.4 Customizable technologies for bodily ownership

A key integration challenge is to develop cost-effective capabilities to customize technologies for the human body to support bodily ownership. Today, most wearable devices follow a one-size-fits-all approach that supports the production of large numbers of devices at low cost. However, this approach does not allow for easy customization of devices for different human body shapes and sizes, and, in turn, this lack of easy customization limits our capacity to influence bodily ownership. For example, an artificial limb will probably facilitate a much lower degree of bodily ownership if it is too large or too small compared to the rest of the body. Prior work, including research into EMS calibration (Knibbe, Strohmeier, Boring, & Hornbæk, 2017) has established that customization for different body shapes can be beneficial. While these approaches put the customization into the hands of the designer, we note that end users can also perform customizations. For example, prior research has examined printed (Steimle, 2015) and cuttable (Olberding, Gong, Tiab, Paradiso, & Steimle, 2013) electronics, as well as 3D printing (MacDonald & Wicker, 2016), that allow end users to produce one-off, customized devices tailored specifically to their body.

The challenge of customization is not restricted to instrumental aspects; it also relates to experiential aspects. Based upon our understanding of the cultural practice of body decorations (DeMello, 2007), we contend that the aesthetics of customizations can have a significant effect on the facilitation of bodily ownership. In this respect, we point to early developments around interactive beauty products (Vega & Fuks, 2013) and aesthetically informed on-skin devices (H.-L. C. Kao et al., 2016; Lo et al., 2016; Weigel et al., 2015). We believe that giving the end-user the ability to customize their device, both aesthetically and to the particularities of their own body, would represent a positive advance in integration design and its ability to facilitate bodily ownership experiences.

7.4.2.5 Communicating with the environment and bodily agency

Our bodies are not isolated, they are shaped by their interactions with the environment. Therefore, the design of integrated devices needs to consider the environment in which they are used. However, unlike analog limbs that concern themselves only with the physical space (e.g. coating the limb in non-slippery material to enhance gripping actions), integrated devices also need to consider the digital or virtual environment. For example, an integrated device might benefit from communicating with sensors in the environment, or even sensors on other people. The device might also benefit from being able to communicate with sensors on other parts of the user's body. The device might also need to connect to the internet to backup data, store data in the cloud, and so on. Making such connectivity feasible and practical is an open challenge that is influenced by (and has an influence on) data rates, privacy, and security, among other things. Energy management is also important, and research has suggested that there are opportunities to harvest body energy to address some of the associated challenges (Sazonov, 2020).

These technical advances raise interesting questions regarding bodily agency. For example, if the human body can communicate in these new ways, how do we manage agency over that communication? On the one hand, backups should occur without requiring user input. On the other hand, if the integration system connects the user's body to nearby wireless networks without the user's authorization, this can raise security issues. Similarly, if a user's body area network communicates with other nearby body area networks without an explicit request and authorization, the user's perceived sense of their autonomy over their body could be affected.

8. CONCLUSION

To conclude, Human-Computer Integration (HInt) is an exciting new paradigm within human-computer interaction. HInt provides strong evidence of the rapidly growing interest in integration between the human body and the computational machine. This growing interest is fueled by technological advances, such as the improved affordability, availability, miniaturization, and efficiency of sensor and actuation devices. However, while these technological advances are important for HInt, the notion of integrating the human body with the computational machine raises societal and ethical questions, not just engineering questions. In this respect, we aimed to articulate the key challenges HInt faces. These challenges need to be addressed if integration is to mature into a stable and persistent research paradigm, sequentially enabling researchers and designers to leverage the associated opportunities for the benefit of a wide range of application domains.

It is important to see this article not as a final conclusion, but rather, as a current examination of the state of the field that eventually will evolve over time. We acknowledge the likelihood that new challenges will arise in the future in response to emerging technologies, sociocultural change, and advances in design knowledge and the human sciences. Furthermore, we are also aware that we have not yet fully examined technology's potential to "deconstruct" aspects of our bodily experiences, and to reassemble them in new human-computer integration constellations. For example, systems could disembody ourselves from our voices (L. A. Takayama, 2008) but re-integrate these voices with other parts of our body. The result of such deconstruction could be very intriguing, novel human-computer integration experiences.

In this article, we highlighted that integration does not just carry the potential to provide benefits, it could also be used to deliberately "make" people take undesirable actions. Consequently, we believe it is important that these discussions of negative future trajectories are had now, so that the risks can be debated with the objective of utilizing integration for good. To achieve such positive outcomes, academics, industry, regulators and end users need to collaborate to carefully consider all the individual and societal implications of their upcoming designs. As part of such an undertaking, existing methodologies such as "Dark Patterns" – patterns in which users are deliberately deceived via interactive technologies – could prove useful in identifying the negative potentials of related fields (Greenberg et al., 2014). We hope that our article provides useful information in structuring such future investigations and steering integration toward a positive future.

On a final note, we are very excited about the potential for integration between the human body and the computational machine. We believe integration will have numerous benefits well beyond what we currently assume interactive systems can offer, and ultimately, that integration will change how people experience the world. We hope that our article gives existing researchers in the field a structured articulation of the current challenges, while providing a useful guide to novice investigators who are curious about entering the field. Ultimately, with our work, we aim to support people contributing to the future of Human-Computer Integration.

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