Towards Understanding the Design of Intertwined Human-computer Integrations

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Human-computer integration is an HCI trend in which computational machines can have agency, i.e. take control. Our work focuses on a particular form of integration in which the user and the computational machine share agency over the user’s body, that is, can simultaneously (in contrast to a traditional turn-taking approach) control the user’s body. The result is a user experience where the agency of the user and the computational machine is so intertwined that it is often no more discernable who contributed what to what extent; we call this “intertwined integration”. Due to the recency of advanced technologies enabling intertwined integration systems, we find that little understanding and documented design knowledge exist. To begin constructing such an understanding, we use three case studies to propose two key dimensions (“awareness of machine’s agency” and “alignment of machine’s agency”) to articulate a design space for intertwined integration systems. We differentiate four roles that computational machines can assume in this design space (angel, butler, influencer, and adversary). Based on our craft knowledge gained through designing such intertwined integration systems, we discuss strategies to help designers create future systems. Ultimately, we aim to advance the HCI field’s emerging understanding of sharing agency.

CCS Concepts: Human-centered computing→Interaction paradigms

Keywords: Bodily experience, shared agency, embodiment

1 INTRODUCTION

The human-computer integration paradigm has recently gained attention in the interaction design community (Farooq & Grudin, 2016; Mueller, Lopes, et al., 2020). Unlike traditional interactions, which mostly rely on a turn-taking command-execution style (“Computer, what is the weather on Sunday?”), human-computer integration embraces the fact that

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computers can increasingly take control and "act with autonomy" (Farooq & Grudin, 2016): "There is a bad weather warning, I will cancel your boat hire for this afternoon".

In particular, there are emerging *bodily* human-computer integration systems in which the computational machine "extends the experienced human body" (Mueller, Lopes, et al., 2021; Mueller, Lopes, et al., 2020). This extension allows the computational machine and the human body "to act on each other physically", i.e., assuming control over elements of each other's form or function, most often through actuation technology (Andres, Hoog, & Mueller, 2018). Such an ability to take control has most recently been discussed in light of technological advances such as artificial intelligence that make such integrations much more feasible than before (van Berkel, Skov, & Kjeldskov, 2021). An example of such a system is the robotic hand extension (Leigh & Maes, 2016): it can support a user's intention to lift something (for example, if the user's hand is not big or strong enough to lift an object on its own), but also work against the user's intention, such as when pushing the user's hand away if the user is about to grasp their mobile phone to check social media as a way to procrastinate.

We are interested in systems that allow the computational machine and the user to share agency over the user's body, that is, can simultaneously (in contrast to a traditional turn-taking approach) control the user's body. As such, we are focusing on the non-turn taking way of "bodily control" in human-computer integration (Mueller, Lopes, et al., 2021) and investigate it in relation to shared agency. This shared agency has previously been discussed in HCI, but mostly from a non-embodied perspective, hence we extend this prior work through a bodily lens (Allen, Guinn, & Horvtz, 1999; Bradshaw et al., 2003; Horvitz, 1999; Keyson, de Hoogh, Freudenthal, & Vermeeren, 2000; Mueller, 2002; Mueller & Agamanolis, 2007; Mueller, Agamanolis, & Picard, 2002, 2003; Mueller, Andres, et al., 2018; Mueller & Berthouze, 2010). We call the result *intertwined integration*. We use the word "intertwined" because it is often impossible to attribute the locus of control to either the user or the computational machine. In other words, the user experience is one where the agency of the user and the computational machine is so intertwined that it is often no more discernable who contributed what to what extent (Danry, Pataranutaporn, Mueller, Maes, & Leigh, 2022). As such, it is difficult to unpack the degree of contribution provided by each agent, giving rise to the question: "Was it me or the computational machine who just did that to/with my body?"

Common, daily interactions with computers can already involve experiences where agency is shared. For example, when drawing with a stylus on a tablet, background processes turn scribbles into smooth lines. Similarly, word processing software autocorrects common typing errors. Experiences like these have been investigated and conceptualized as computational autonomy (Beavers & Hexmoor, 2003; Bradshaw et al., 2003), mixed-initiative (Allen et al., 1999), human-agent interaction (Bradshaw, Feltovich, & Johnson, 2011), and the H-mode (K. H. Goodrich, Schutte, Flemisch, & Williams, 2006). We note that these prior conceptualizations of the human-machine relationship presume a dichotomous relationship between system and user. We believe that these limited perspectives are most likely due to the traditional, often screen-based, interactions these conceptualization investigations considered. In contrast, we find that technological advancements, such as robotics from a hardware side and artificial intelligence from a software side, bring new opportunities to share agency – especially involving the human body – and result in novel experiences. This insight is partially inspired by shared agency work around collaborations with robots, yet distinct, noting that collaborations with robots is a wider research area not specifically interested in the investigation of shared agency over the user's body, nor does it necessitate simultaneous interaction between the human and the robot as intertwined integration does (Green, Billinghurst, Chen, & Chase, 2008; Hoffman, 2019; Matheson, Minto, Zampieri, Faccio, & Rosati, 2019; Nyholm, 2018; Robla-Gómez et al., 2017).

We believe that engaging the human body in new ways could offer various advantages, such as enriching self-awareness and self-actualization experiences. Taking these further down the line, we also believe these enrichments could facilitate health benefits. For example, becoming more self-aware is associated with the potential to improve mental health by increasing one's ability to feel one's movements and sensations (Fogel, 2013). Furthermore, it is believed to help with obesity, eating disorders and some forms of cardiovascular disease, as these can arise from a lack of awareness of the movements of the body, such as when people overeat as they do not sense when their stomach is full (Fogel, 2013). Similarly, the stress of work situations can lead to a diminished awareness of muscle tension that can lead to deterioration in the long term (Fogel, 2013). Furthermore, it is believed that enriched awareness of the body can help regulate its physiological functions (Fogel, 2013).

Furthermore, research suggested that nurses who are more self-aware deliver better care to their patients (Rasheed, Younas, & Sundus, 2019). Lastly, it is believed that enriched self-awareness can be beneficial to practitioners of the meditative disciplines, such as yoga, tai chi and many martial arts, as it helps them to understand how their practices can affect mental and physical health and wellbeing (Fogel, 2013). In HCI, prior work has drawn on these findings and used computational machines to engage the human body in a way to promote physical activity, with the aim to promote physical health (Göbel, Hardy, Wendel, Mehm, & Steinmetz, 2010; La Delfa et al., 2020; Lieberman, 2006; Mildner & Mueller, 2016), which inspired us further.

However, there is limited knowledge available to assist the designers of intertwined systems. Prior work laments that design knowledge for intertwined systems is needed (Grudin, Höök, Maes, & Mueller, 2018; Leigh, Sareen, Kao, Liu, & Maes, 2017; Mueller, Kari, et al., 2020; Mueller, Lopes, et al., 2021; Mueller, Lopes, et al., 2020). However, individual efforts have contributed to a better understanding of particular aspects of bodily integration. For example, engineering work around power consumption optimization has assisted with efforts to power actuators on the human body (Bareket et al., 2016; Britton & Semaan, 2017; Jovanov, 2006), and theoretical investigations into the conceptual boundary between the human body and a computational machine have assisted discussions of humanistic issues relating to cyborg futures (Clark, 2001; Haraway, 2006; Roden, 2010). Building on this, our work takes a user experience perspective to construct an initial understanding of the design of intertwined systems. This initial understanding underpins our contribution: a framework incorporating a design space that helps articulate and categorize the key roles the computational machine can take in intertwined systems. The design space will aid designers aiming to create future systems. It is complemented by a set of design strategies based on our craft knowledge gained, in part, through developing and studying a set of case studies. We acknowledge that we are presenting the results of an early investigation into this developing field of research and not a conclusion. Nevertheless, even with this initial understanding, we hope to extend knowledge about the design of intertwined systems.

We believe our work can be useful for a range of professions. For example, design practitioners can use our work to design future systems and seek starting points on how to go about creating them. Researchers can use our work when wanting to analyze and evaluate existing intertwined experiences. Engineers and system developers might be inspired by our work to identify other user experiences that their existing technologies could facilitate. Lastly, HCI designers can use our work when aiming to advance their existing systems that currently give agency only to either the user or the system by now also allowing to share agency, enabling new user experiences.

We follow this introduction with a section on related work, to identify the gap in design knowledge and subsequently articulate the research question that aims (at least partially) to fill this gap: how to design intertwined systems? To answer this research question, we present the intertwined framework. The framework consists of a design space of intertwined systems along with a set of strategies for the design of future systems. We illustrate the design space through three case studies. Two dimensions span the design space: "awareness of machine's agency" and "alignment of machine's agency". Using the four quadrants of the design space, we identify four key roles the computational machine can take. We then articulate a set of strategies to guide practitioners in future systems design. We conclude the article with a section on our work's limitations and identify avenues for future research.

2 RELATED WORK

We have primarily learned from prior work on agency, the augmented human, and bodily interactions. We articulate how each has helped us to at least partially answer our research question.

2.1 Learning from prior work on agency

Given that we are examining systems where the computer can exhibit some form of agency, we have learned from prior work that discussed aspects of agency or demonstrated systems that seemed to exhibit agency. In particular, we have learned from prior investigations into shared agency between computer and user. For example, prior work on "mixed-initiative interactions" has guided our work (Bradshaw et al., 2003). Bradshaw et al. proposed a set of dimensions to describe such interactions. The authors argued that we should differentiate between actions a system can perform and actions that a system is allowed to perform. This differentiation speaks to our work in so far as it highlights that a system might be able to help a user but should not do the work entirely "for" the user, effectively replacing the human.

We have also learned from prior work that highlighted how system agency could sometimes act in the foreground and at other times in the background (Jacob et al., 2008; Ju & Leifer, 2008; Serim & Jacucci, 2019). Our work speaks to this distinction by considering the user's awareness of the system's agency. If a system's agency operates in the background, a designer might choose to make the user aware of it. Similarly, if a system's agency operates in the foreground, a designer might choose to conceal it from the user by, for example, directing their attention towards something else.

Prior work on agency also proposed that the effort users put into a particular interaction with a system can be described on a focused-casual continuum (Pohl & Murray-Smith, 2013). Like the authors of this work, we also look at continua rather than distinct separations. However, we do not start with a view on how focused or casual the user approaches a system. Instead, we consider the extent to which a user is aware of a system's agency as we believe awareness of control is key to the resulting user experience.

We have also learned from prior work that argued that we should see the shared agency between a system and a user as dynamic rather than static (Allen et al., 1999). In other words, at a point in time, the user might have primary control, then the system might take more control, just before releasing this control again to the user, and so on. In response to these characteristics, our work highlights that the awareness and alignment of agency are usually not fixed but rather sit along two dimensions that can vary during the interaction.

Prior research also taught us that designing for shared agency is not easy (Horvitz, 1999). Horvitz argued that designing for situations when the user and when the computational machine is in control (and the transitions between) requires careful consideration (Horvitz, 1999). Since then, other interface research beyond the computer desktop has recognized that sharing agency has potential; for example, IoT devices like an intelligent thermostat need to be controllable by a user, but also by the smart house, and designing for both is not easy (Keyson et al., 2000). Such shared agency has also been investigated in other application domains, like robot-assisted surgery (Abbink et al., 2018). We therefore also learned from prior work around human-robot teaming and human-robot collaborations. Although robots generally do not take control over the user's body (a specific form of control we are interested in), we note that sometimes, when humans and robots work physically close with one another, it can occur that the robot takes control over the human body. This can be unintentional, for example when the robot malfunctions and moves in a way that pushes the user out of the way. Or it can be intentional, for example, when the robot and the user collaborate in an embodied way, such as when the robot would grab the user's hand to guide it towards a particular goal. Such human-robot teaming or collaborations have been investigated in the literature before. For example, prior work has looked into how humans collaborate in order to apply it to human-robot collaborations (Shah & Breazeal, 2010). This work highlighted that speed of response is important for successful collaboration, which speaks to our intertwined systems in so far as this notion draws from a speedy response that is perceived almost instantly, in contrast to the traditional command-response paradigm that is generally based on a slower turn-taking approach. We were also inspired by prior work that examined what we can learn from human-animal relationships in order to design human-robot collaboration systems (Billings et al., 2012). The authors argued that "trust" is a key ingredient and suggest designing systems that users trust. We similarly hope that our users trust the intertwined devices we are interested in, however, leave the establishment of such trust for future work. Nevertheless, we discuss later in this article ethical issues that speak to aspects of trust, so hopefully our work can be helpful in furthering such future work.

Similarly, prior work by Robla-Gomez examined human-robot collaborations and found that there is potential for physical harm when humans and robots work together in close proximity (Robla-Gómez et al., 2017). We agree and hence are thankful for the authors' suggestions on how to consider safety in these situations. We tried to consider these safety considerations in our work also as, although our devices are significantly smaller and less powerful, they have potential to produce harm. In consequence, we propose to designers to also look at these safety recommendations when designing intertwined systems.

We also learned from a recent review on human-robot collaborations that highlighted that, although more and more research in this area has emerged in recent years, a complete understanding of how to design for successful human-robot collaborations is still lacking (Wolf & Stock-Homburg, 2020). In particular, the authors point out how to manage the "control" both the robot and the user might exhibit at various points in time is still underexplored. We hope that with our work, we contribute towards a more complete understanding of control by focusing on agency in intertwined systems.

Prior work on human-robot collaborations more generally found that investigating successful collaboration design could have huge potential (Matheson et al., 2019). In particular, the authors point to technological advances that allow robots to work in close proximity to humans, not requiring to be placed in protective cages anymore. This allows for new ways to work together, going from a simple co-existence to cooperation and ultimately to collaboration. This aligns with our observation of interactions having moved from a command-response paradigm to a paradigm of integration where the computational machine and the user collaborate. In contrast to the work by Matheson et al. (2019) though, we, in this article, focus on a particular form of collaboration, that is an embodied form where the computational machine and the human body is intertwined in a way to be able to travel with the user. We believe that this allows for novel experiences not possible in collaborations where the robot is mechanically fixed to a particular location.

Furthermore, a literature review (Tabrez, Luebbers, & Hayes, 2020) found that prior work has proposed that "fluency", or a "coordinated meshing of joint activities between members of a well-synchronized team" (Hoffman, 2019) can contribute to a successful human-robot collaboration. This fluency speaks to intertwined systems as we are also looking at the "meshing of joint activities" in our intertwined systems where one can no longer discern who contributed what to what extent.

Research in human-robot collaboration also found that "situational awareness and a common frame of reference" could be a key ingredient, suggesting that augmented reality could help with this (Green et al., 2008). Although we did not investigate traditional augmented reality with its headsets in this article, prior work has considered augmented reality headsets in what we would consider intertwined systems (Semertzidis et al., 2020). Nevertheless, we believe that our focus on intertwined systems that are wearable speak to the notion of situational awareness and a common frame of reference, as the system itself is positioned on the body and hence can be seen by the user in relation to it, rather than, for example, a stationary robot like in most examples of human-robot collaboration mentioned in the literature survey papers described above.

Furthermore, research into autonomous cars has emerged that highlights the challenge of sharing agency, in particular during handover situations, reflecting on the increasing sensing capabilities that allow to give cars more and more control. Efforts are underway to understand how to manage agency between the car and the driver, in particular, how to handle the handover when the self-driving car needs driver intervention (Abbink et al., 2018). So far, these investigations appear to focus mostly on turn-taking scenarios, where either the car or the driver is in control at any one time. However, simultaneous control by the self-driving car and driver seems to become more and more prevalent to consider (Abbink et al., 2018); a development to which our work might contribute. Beyond the automotive application domain, we note that research has emerged that highlights the potential of shared agency also for creative endeavors, going beyond instrumental needs, including game design (Deterding et al., 2017), speaking to our focus on alignment where the system can be an opponent or adversary, which we discuss later.

We are also inspired by research that aimed to provide design guidance by looking at non-digital, analogous shared autonomy examples. For instance, previous research suggested looking at horse riding to design such systems (Höök, 2010). You can, for example, relinquish control to a horse and shift attention to other simultaneous tasks like reading a map, or you can take greater control over the horse (K. H. Goodrich et al., 2006). This metaphor aligns with the experiences participants of prior research had with intertwined eBikes (Andres et al., 2016; Andres, Kari, Kaenel, & Mueller, 2019; Andres et al., 2020; Andres, Semertzidis, Li, Wang, & Mueller, 2022). This speaks to our work in regard to the alignment of agency: we also consider cases in which the system might work *against* the user, just like a horse might wish to move in a different direction and work against the rider.

Furthermore, we are guided by prior work that highlighted that observability of a system's agency is an important factor for the resulting user experience (Bradshaw et al., 2011). This consideration is reflected in the dimension of "awareness" in our framework. However, we also point out that there are cases in which reducing such awareness – leading to reduced observability – can be beneficial for specific user experiences, like games.

We also learned from prior research by Beavers and Hexmoor that suggested describing systems with agency using two dimensions: individual capacities and individual rigidity (2003). We also use two dimensions, but, like Beavers and Hexmoor, these address awareness of agency and the alignment of agency. Our interest is in user experiences rather than autonomous systems' interactions.

We also learned from work on agents that exhibit some form of autonomy. Prior work highlighted the close relationship between autonomy and agency, arguing that autonomy is achieved by motivating agency, or, more precisely, that "autonomous agents are agents with motivations", whereas "agents are objects with goals" (Xu & Shatz, 2003). This conceptualization allowed Bartneck and Forlizzi to categorize robots based on their level of autonomy (Bartneck & Forlizzi, 2004). They defined autonomy as "having the technological capabilities to act on behalf of humans without direct input from humans. Autonomy is expressed as a continuum ranging from no autonomy, to some autonomy, to fully autonomous" (Bartneck & Forlizzi, 2004). We also regard agency to be on a continuum. Our article extends this prior work by exploring which aspects of a system's agency (such as exhibited by a fully autonomous robot) contribute to an intertwined experience.

Similarly, Goodrich et al. suggested that there are different levels of autonomy to describe the extent to which robots can act on their own accord; ranging from the robot offering no assistance (the user does everything) to the robot doing everything and acting autonomously (ignoring the human) (M. A. Goodrich & Schultz, 2008). In the middle of this range sit systems in which, for example, the computer informs the human about an action it performed. The level of automation distinguishes between the system informing without being asked and informing only when being asked. This distinction aligns with our conceptualization of varying levels of awareness. The user has more awareness when they are informed without asking (or being asked) and less awareness when they must ask.

We also note that prior work by Janiert and Stolterman discussed aspects relevant to our investigation in their work on trying to understand "interaction" (2017): although they focus on smart objects more generally, they also touch upon devices that could be described as being intertwined. In particular, the authors consider "agency" as key ingredient (like we do below), while noting that agency is a "complicated notion". With our work, we hope that we can contribute towards unpacking this complicated notion that seems to be so fundamental a bit further. Furthermore, we note that the authors stress "awareness" as a key ingredient for any interactivity. Similarly, we are also considering "awareness" in our framework below, and examine its particular role in intertwined systems, hence enhancing our understanding of awareness in a particular case of interactivity. In particular, we unpack the user's awareness of the computational machine's agency by placing it along a dimension, hence examine high and low levels of awareness a user can have over a machine's agency.

2.2 Learning from prior work on the augmented human

We also learned from prior work on the augmented human. This work goes back to 1960, at which time Licklider proposed that we need a "very close coupling" between computer and user, which we view to be a precursor for intertwined systems (1960). A long line of wearable computing projects followed; they mostly equipped the human body with sensors. Sensors are certainly useful for intertwined systems. However, sensors tell only half the story, as they mostly lend themselves to the traditional paradigm of the user issuing a command to the computer, albeit now, they can do so on the go that resulted in the wearables trend (Marshall, Dancu, & Mueller, 2016). The ubiquitous computing agenda (Weiser, 1993) has taught us that we can see computing conceptually as either pointing towards or away from the user's body: Weiser used it to argue why the ubiquitous computing approach is different to a virtual reality approach. Similarly, we put the human body in the center of the experience, following a body-centric computing perspective (Mueller, Andres, et al., 2018). The idea of human augmentation (Raisamo et al., 2019) aims to go beyond wearables by proposing that we use technology's unique affordances on the human body. For example, Schmidt et al. (2017) proposed that human augmentation can benefit from providing in-situ information to the user. Svanaes et al. (2016) went further, proposing that these systems can provide in-situ information and experientially extend how people perceive their bodies. Leigh et al. (2017) highlighting that we need to consider how users perceive their augmented bodies when designing such systems. For example, users can feel hindered by a system (which we cover under our "adversary" role, discussed later), even though the system appears to be supportive. We learned from these prior works that equipping the human body with technology affords unique opportunities that require careful design. However, research has not yet articulated how to design for these opportunities, especially where agency is shared simultaneously.

We also learned from engineering and artistic projects that led to intertwined systems. For an arts performance, Stelarc (2020) developed a robotic arm that functioned as his third arm. The public could control the arm over the internet. Stelarc aimed to raise questions about who is in control of his body, which speaks to shared agency. Lopes et al. (P. Lopes, Yuksel, Guimbretiere, & Baudisch, 2016) used electrical muscle stimulation to give control over the human hand to a machine, allowing to conduct computational tasks – that the user would not be able to do without a computer – executed by the user's own hand. Marshall et al. (2011) also allowed a computer to control the human body. The authors developed a mechanical bull fairground ride that shook the rider around based on their breathing. As the rider could only slow down their breathing but not entirely stop it, they experienced limited agency. This experience could be engaging, the authors argued, in the entertainment context for which they had designed the ride.

We have learned from these system works that taking control over one's body can facilitate intriguing bodily experiences. However, because most prior works often looked only into turn-taking interactions, where either the user was in control or the computer, they missed opportunities for agency to be shared (Patibanda et al., 2021). Furthermore, these prior works often also did not examine the resulting user experience. Consequently, our knowledge about the design of such intertwined systems remains incomplete.

2.3 Learning from prior work on bodily interactions

We also learned from prior HCI work on embodied interactions (Dourish, 2001), which argued against a mind-body dichotomy (like Norman did with cognitive engineering (1986)) and emphasized that the body and mind are expressions of a single continuous system, speaking directly to our focus on intertwined systems. In particular, Klemmer et al. (2006) argued that designing for the intertwined mind and body is advantageous; a call we respond to with our focus on intertwined systems, which encompasses a more holistic view on the coming together of human and computational machine.

Wakkary et al. (2016) argued that we are sometimes "unselfconscious" of our interactions. This aligns with our focus on awareness, where we consider whether users are aware (or not, i.e. unselfconscious) of a computational machine's agency. Similarly, Serim and Jacucci (2019) analyzed implicit interactions and noted the importance of agency in such investigations, which speaks to our dimensions around agency. The authors reviewed meanings of implicit, including "unintentional, attentional background, unawareness, unconscious and implicature". With a more refined understanding, the authors argued, it is possible to better understand concepts such as "mixed-initiative", "proactive", "adaptive" and "automatic". These terms align with our focus on agency, where the user is not always in control. Many intertwined experiences make use of implicit interactions, so we extend this prior work by discussing the resulting user experiences.

We also note that there is an increasing trend in HCI that aims to connect our bodies "more deeply" to computers (Steve Benford et al., 2020). For example, Mueller et al. proposed a framework to aid interaction designers when designing for the active human body (Mueller & Agamanolis, 2007; Mueller & Agamanolis, 2008; Mueller et al., 2002, 2003; Mueller, Agamanolis, Vetere, & Gibbs, 2009; 2011). However, the authors were mostly focused on sensing bodily actions (Mueller et al., 2011), whereas we are interested in agentially sensing and actuating the human body.

Emerging HCI work has also valued the subconscious in our interactions with computers, given that many intertwined interactions can occur at a sub-conscious level. For example, Adams et al. (2015) argued that we should design "mindless computing", where the system tries to influence the user without their conscious awareness. Similarly, Pinder et al. argued that we should design for conscious interactions *and* have systems control subconscious interactions (2018). Prior work (Mueller, Lopes, et al., 2021; Spiegel, 2019) applied this notion of designing for the subconscious to human body-focused interaction design practice, arguing that we can learn from bike riders, specifically, how their conscious and subconscious interactions with the bike lead them to become "one" with it. This becoming "one" speaks to intertwined systems. We extend this prior work to the examinations of systems that have agency, to underpin a more nuanced understanding of the associated user experiences.

We are also inspired by work on somaesthetics (Höök, 2018), as the authors' designs engage with the notion of control over one's body. For example, an interactive light aims to facilitate looking "inwards" by varying its brightness and encouraging control over one's breathing (Höök, Jonsson, Ståhl, & Mercurio, 2016). Similarly, an interactive yoga mat with built-in heating elements aims to help users control the attention they give to different parts of their body (Höök et al., 2016). While these systems play with the notion of bodily agency, which resonates with our work, they are mostly directed inwards. In contrast, we are examining all intertwined experiences, and these examinations are directionally agnostic.

We are also inspired by whole-body interaction research (England et al., 2009) that highlighted that designing for the active human body requires different design knowledge than traditional desktop interactions (Hamalainen, Marshall, Kajastila, Byrne, & Mueller, 2015; Jensen & Mueller, 2014; Mueller et al., 2003; Mueller & Gibbs, 2006, 2007; Mueller, Marshall, Khot, Nylander, & Tholander, 2015; Mueller et al., 2012; Mueller, Vetere, Gibbs, Edge, et al., 2010; Mueller, Vetere, Gibbs, Agamanolis, & Sheridan, 2010; Nylander, Tholander, Mueller, & Marshall, 2014, 2015; Pijnappel & Mueller, 2013, 2014). Work by Schiphorst (2009) and Loke et al. (2013) aimed to construct such knowledge by understanding dance to inform interaction design. These dance works highlight the importance of considering how people feel during these interactions, which resonates with our focus on the user experiences of intertwined systems.

Hummel et al. argued for the consideration of bodily movement as design material (2007). We extend this prior work by adding knowledge about the design of systems where the human body and technology merge as intertwined design materials (Wiberg, 2018).

Hämäläinen et al. (2015) argued for the consideration of gravity as a way to "move" the human body. The authors cited examples such as skydiving, where gravity pulls the user's arm down (and the whole body), but the user aims to move the arm against it as a way to steer the flight in a certain direction. We consider such contrasting movement directions in our framework under the "alignment" dimension and extend this prior work by looking at computational machines that might provide a "pull" of the human body in any direction, not just downwards.

We are also inspired by Segura et al. (2013) who highlighted that the design of bodily interactions should not overlook social aspects. We consider social aspects in our framework when we discuss implications for the associated user experiences. Although most intertwined systems are personal because they are fitted to one person (and often customized), they are still used within a social context (Mehta, Khot, Patibanda, & Mueller, 2018). Furthermore, we argue that intertwined system designers should consider social aspects (Altimira et al., 2016; Mueller & Karau, 2002) because these systems are often used for a long period and hence might move through a variety of social contexts.

We are also aware of the view on HCI from an entanglement theoretical perspective as put forth by Frauenberger (Frauenberger, 2019). Frauenberger argues that we should move towards a view on HCI as intimate relationships between various agents where humans and digital artefacts are seen as agents in a networked relationship. From this perspective, humans and the digital designs are intertwined entities affecting each other in return. Acknowledging this understanding of a causal relationship between humans and technology, we view intertwined systems sitting in a design space of mutual human-technology configurations in which the technology as an agent has agency – an agency that the user can be more or less aware of.

In summary (table 1), our investigation of prior work revealed that some systems and frameworks offer at least partial guidance on the design of intertwined systems. However, existing systems do not provide extensive insights into the associated user experiences as they often stem from engineering perspectives that focus on technical feasibility. On the other hand, existing frameworks are either theory-focused, falling short in terms of design implications or empirical validation, or their concerns with shared agency on a bodily level are tangential and do not address design issues. Consequently, there is still limited available knowledge for the design of intertwined systems, and without it, the field will be unnecessarily restricted and unable to unfold its potential. With such knowledge, more systems can be designed in better ways, we believe, helping the field to thrive. Therefore, our article aims to contribute towards filling this gap in knowledge by aiming to answer the research question: how do we design intertwined systems?

Our article aims (or at least begins) to answer this research question by presenting three systems as case studies: an intertwined ride (through an eBike's motor control); an intertwined eating experience (through shared bodily extensions in the form of additional robotic arms for feeding); and an intertwined bodily support system (in the form of an active exoskeleton). We combine personal craft knowledge from having designed two of these systems, learnings from associated studies, and insights from prior work, to construct a framework that presents a first understanding of how to design intertwined systems.

Table 1. Summary of learnings from prior works

Prior work	*Learnings*
Agency	Agency lies on a dimension
	Agency is often dynamic, not static
	Agency considerations can raise ethical concerns
	Shared agency is complex yet not fully understood, but represents a great opportunity for intertwining humans and machines
	Shared agency can be concerned with conscious but also subconscious actions
	Shared agency between robots and bodily human actions is an underexplored area
	Looking at traditional shared agency experiences, such as with animals, might be beneficial
	Awareness of a system's agency can be important
Augmented human	Augmented human research suggests going beyond simply attaching sensors to the human body
	More recent investigations into augmented human consider actuators instead of just sensors
	Current research focuses mostly on turn-taking approaches to shared agency in order to reduce complexity
	Approaches to shared agency beyond turn-taking within augmented human projects hold great potential
Bodily interactions	There is an increased focus on connecting human bodies with computers
	Learning from bodily interactions such as those exhibited with sports equipment could inform understandings of becoming "one" with a system
	Bodily interactions should be investigated with the user experience in mind
	Alignment of movement in bodily interactions can be key
	Bodily interactions as part of shared agency are underexplored

3 THREE CASE STUDIES

We now present three systems as case studies. Two of the systems were developed by us at different times by different people with different external partners, the third system is a commercial system to complement our own work. The three systems use different technologies, engage different application domains and target different aims. We chose a commercial system to complement our case studies in order to demonstrate the wider applicability of our thinking around intertwined systems and also to show that our design space covers a wide range of systems, not just those developed by us. Furthermore, this might also suggest that our work might have direct implications readily applicable to industry.

We briefly characterize each case study below (Table 2).

Table 2. Three case studies and their key characteristics

System	*Application Domain*	*Technology*	*Aim*
Ari	Mobility	Electrical engine and mobile phone sensors	Promoting cycling
Arm-A-Dine	Eating	On-body robotic arms and camera	Supporting shared eating
EduExo	Education	Motor and electromyography (EMG) sensor	Teaching exoskeleton principles

3.1 Case study 1: Ari

We believe that electric bikes are the future of urban mobility, hence we were interested in investigating what opportunities intertwined design can bring to eBike riding experiences (Andres et al., 2016; Andres et al., 2018; Andres et al., 2019; Andres et al., 2020; Andres et al., 2022).

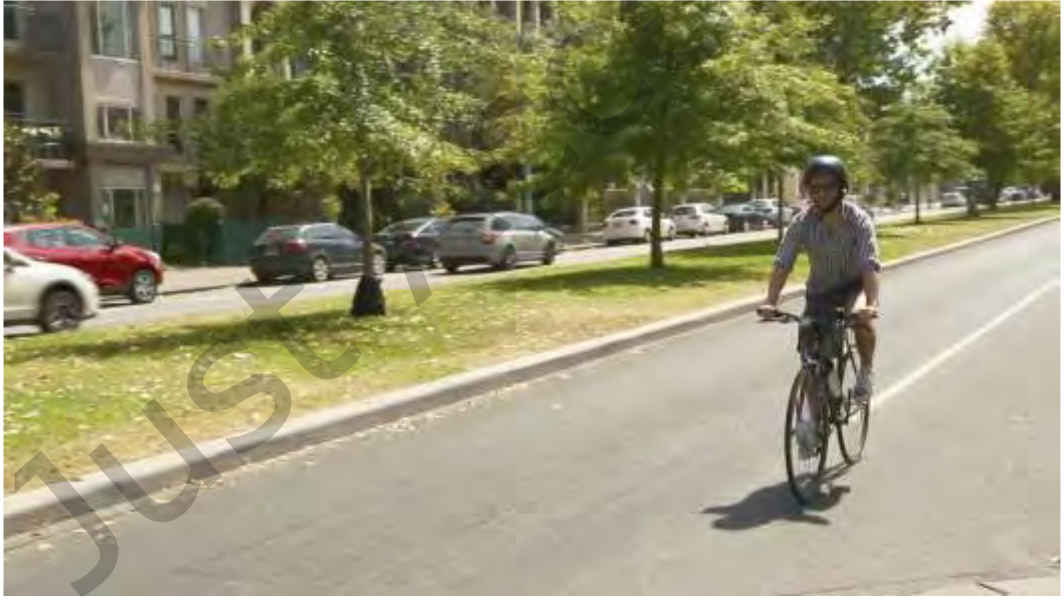

Figure 1: Ari is an eBike that uses its engine to help the rider catch green lights

Early eBikes added a motor to an existing bike, with the motor being controlled by a lever, similar to a throttle, which allowed the rider to choose crudely how much power the battery provided to the engine. These levers often operate on a 1-2-3 level setting. The rider would use the levers to issue a command to provide engine support, meaning that these systems sit very much within the traditional command-execution interaction paradigm. More recent eBikes sense pedaling efforts, and the engine provides what is called pedal-assist only when the rider is pedaling.

Our eBike called “Ari” (Figure 1) takes a different approach. Ari uses traffic light data and the rider’s speed to modulate engine support to help the rider reach the next traffic light on green, thereby reducing the frequency at which the rider must stop. As such, Ari aims to offer a smooth cycle through the city that seems to welcomingly "open up" as the rider can cycle through a wave of green traffic lights.

By combining the city authority's traffic light data and the bike's speed data, sensed by a mobile phone, the system can calculate the distance to the next traffic lights. Based on this information, the eBike can provide more engine support and accelerate, so that the rider reaches each set of traffic lights at precisely the time when the lights are green.

We conducted a study with 20 participants (6 female, 14 male, aged between 23 and 48 years with an average age of 36 years) (Andres et al., 2019). During the interviews that we conducted with the participants, they described experiences that speak, for us, to intertwined experiences, namely the collaborative working together between the eBike and the rider to make the next set of traffic lights at green. For example, one participant said: "*It can sense things that humans can't"*. Here, the rider became aware of a skill that the eBike appeared to possess (sensing traffic light states) that aligned with the rider's intention (crossing lights at green). Another participant described how "*it felt like a guided bike riding, like the bike was my teacher almost*". Here, the rider became aware of the eBike being able to take more control over their ride, such as when accelerating closer to a set of lights to still make it when green. The following statement complemented this: "*It's like your buddy, it knows where the traffic lights are at, but it doesn't have eyes. You have eyes, so you're like, 'I'll take care of you. You take care of me', so, 'You do the traffic light thing. I'll make sure we don't hit anything'"*. This suggests to us that the rider became aware of the eBike being able to take more control over the ride (in contrast to a traditional eBike), which they appreciated, as it complemented their own skills (navigating traffic), in other words, their intentions were aligned. Another participant said: "*The bike is not actually capable to determine if it's dangerous ahead or not. Actually, you, as a human, you are equipped with those sensors. The bike has some information that you don't have, and you have the information that the bike doesn't have.*" This takes the above-mentioned sentiment further by highlighting that the rider not only became aware of the eBike's potential to take control, but also that there is some danger to it, for example, if this would be misaligned with their intention, such as breaking in front of an appearing obstacle. We point to recent eBike research that has explored this further in regard to safety, where biosensing has been used to pre-empt dangerous situations (here, a narrowing field of view), to reduce the eBike engine's support in order to enhance road safety (Andres et al., 2020).

3.2 Case study 2: Arm-a-Dine

Figure 2. Arm-A-Dine enables a playful feeding experience through robotic arms

Arm-A-Dine (Figure 2) (Mehta et al., 2018; Mueller, Kari, et al., 2018; Mueller, Kari, et al., 2020) is a playful (Deen et al., 2014) feeding experience enabled through robotic arms. It focuses on the plate-to-mouth action within human-food interactions (HFI) (Deng et al., 2022; Khot, Aggarwal, Pennings, Hjorth, & Mueller, 2017; Khot & Mueller, 2019; Khot, Pennings, & Mueller, 2015a, 2015b; Mueller, Dwyer, et al., 2021; Y. Wang, Z. Li, R. Jarvis, R. Khot, & F. Mueller, 2019; Wang, Li, Jarvis, Khot, & Mueller, 2018; Y. Wang, Z. Li, R. Jarvis, R. A. Khot, & F. F. Mueller, 2019; Wang, Li, et al., 2019a; Wang, Li, et al., 2020; Wang, Li, et al., 2019b; Wang, Li, Khot, & Mueller, 2021; Wang, Li, Khot, & Mueller, 2022; Wang, Zhang, Li, Khot, & Mueller, 2020). The system was inspired by diners often sharing meals and sometimes feeding food to one another. The system explores what role a third arm could play in these activities.

Two Arm-A-Dine diners participate. Each wears a vest equipped with a robotic arm that serves as a third arm during eating. The third arm can autonomously perform grabbing actions and move the food to the diner's or their partner's face. However, it cannot sense the food's location, so the diners need to position their upper body to align with the food on the table. The eating scenario is a casual snacking experience such as often featured at conferences where canapés are served.

After the third arm grabs a piece of food, it feeds the food either to the diner wearing the equipment or their dining partner. This choice is based upon the dining partner's facial expression, which is sensed via a camera embedded in the diners' vests. If the dining partner makes a "happy" facial expression, the arm will feed them. This facial expression could result from the social interaction or because the partner has eaten something pleasant. Consequently, the system supports the dining partner for as long as it senses a happy facial expression. If the system senses a "sad" facial expression – perhaps, because the dining partner has just eaten an unpleasant food item – then the third arm will feed the equipment wearer. If the system can sense neither a positive or a negative facial expression, the third arm will move back and forth between the two participants, as if it was teasing them about who will get the food. After a time, the third arm randomly decides who to feed. This arm movement, where the robot acts autonomously, is experienced by both participants visually, as they can both see the robotic arm moving. They can also hear the motors. The wearer of the vest, however, experiences this autonomy also in a haptic way through the vest, as the movement of the arm changes the weight distribution (especially when the arm extends), affecting the pressure on their chest through the vest.

We conducted a study with 12 participants (5 male, 7 female, aged between 21-27 years with an average age of 24 and a standard deviation of 1.6 years) (Mehta et al., 2018). During the study, we asked each participant to eat casually with their partner. At the end, we asked them to partake in a 20-minute, semi-structured interview together. Participants revealed how the intertwined integration of robotic arms and their bodies engendered a sense of ambiguity, making the experience challenging, fun, and enriched social interactions. For example, one participant said: *"Although I would love perfect arm movement each time – but it is too boring. If the arm is too perfect, then there is no chance of anything going wrong or something unexpected to happen and so there is no element of surprise."* This quote highlights for us two things: first of all, that the wearer was aware that the robotic arm had some form of agency. Secondly, the wearer also realized this agency was not always perfectly aligned with their intention, that is, feeding the food in a certain way: the limitations of the mechanical arm resulted in some impreciseness, creating ambiguity. However, due to the context of eating, this facilitated instances of near-misses, spilling, etc., that contributed to the playful character of the experience. The participant explained how this enhanced their social interactions: *"I think unpredictability of the arm's movement was great and made the eating experience more playful by increasing the conversation time I had with my partner"*. Furthermore, the indecisive movement of the robotic arm, when it was not clear who will be fed next, underlined the potential of moving agency from the wearer (when they have more control over who will be fed next by moving their body) to the robotic arm taking more control, first by moving back and forth in a pre-programmed fashion, then deciding who will receive the food based on a random function: *"The most exciting bit was when the third arm moved strangely in the air. It felt as if the arm was teasing us by fluttering between both our mouths. It was like: 'Wow!' And it felt good to see something like this"*. This participant's description of what they call "teasing" as a result of the system taking control highlights the potential of intertwined systems to facilitate interesting user experiences that go beyond what one would commonly assume when the computational machine takes control.

Giving away partial control to the machine appeared to help participants focus and enjoy actions that they often do subconsciously. For example, one participant said: *"When I think of a normal meal, I do not focus on the act of getting the* *food from the plate to my mouth. I take this act as granted. However, this experience of eating with robotic arms and sharing food with my partner pushed me to focus on those things"*. Facilitating being present when eating aligns with the trend of mindful eating (Arza, Kurra, Khot, & Mueller, 2018; Lofgren, 2015; Nelson, 2017), hence thinking about agency might also support such mindful practices, we believe. Although we leave such investigations for future work, we are encouraged by our participant's quotes who expressed that Arm-A-Dine was able to shift their attention more towards the food: *"It pushed me to put extra effort and attention to the eating process. But when I got the food after twisting, turning and slow movement of the robotic arm, I felt rewarded and satisfied."*

3.3 Case study 3: Exoskeleton

Figure 3. Active exoskeleton "EduExo"

Our third case study is an exoskeleton by the company "Auxivo", a spin-off start-up from ETH Zurich (Auxivo, 2022a) (Figure 3). The particular model we heron refer to is the "EduExo", an active arm exoskeleton. Auxivo is the producer of a series of exoskeletons that, unlike many other exoskeleton companies, have been available in the marketplace for a while. Furthermore, their products are reasonably documented and are based on research that is available in public libraries. There are even videos available that show them functioning in the real-world (Auxivo, 2021). We note that their industrial line consists at the time of writing only of passive exoskeletons, suggesting that the use of active exoskeletons in-the-wild is still underdeveloped. However, the "EduExo" is an active exoskeleton aimed at educators and makers who want to build their own exoskeleton, allowing to gain first-hand experiences using the system. The exoskeleton aims to support arm movement by providing support through the in-built motor, controlled by an electromyography (EMG) sensor. The entire system was designed to facilitate learning about hardware design, electronics, control theory, software design and scientific evaluation according to the producer's website (Auxivo, 2022a). Its customizability and modular structure allow us to envision modifications and future versions that help illustrate our thinking around the framework and also hopefully demonstrates that our design space is more widely applicable beyond our own work.

Prior work has already regarded exoskeletons as lending themselves to supporting human-computer integration (Mueller, Lopes, et al., 2020), here, we examine the "EduExo" for its potential to support intertwined experiences. In most basic cases, the exoskeleton supports the user by aligning the motor's movement with the user's arm. However, it is also possible that the system is not aligned with the user's intention, as a video suggests (Auxivo, 2022b). As the system is designed for educational purposes, all the data the system produces is readily accessible on the laptop in front of the user, hence the user has some in-depth awareness of the machine's agency.

4 OUR APPROACH

Our work did not begin with an intention to prove a particular theory. Instead, we arrived at the framework through our iterative and reflective design practice, in which engagements with designing and theoretical thinking occurred simultaneously in the research-through-design tradition (Dow, Ju, & Mackay, 2013; B. Gaver & Bowers, 2012; W. Gaver, 2012; Mueller, Petersen, & Li, 2022; Zimmerman, Forlizzi, & Evenson, 2007). Specifically, we engaged in discussions around related work, our design practice, and associated studies, cycling back and forth between theory and practice. This approach is not unlike the performance-based HCI method (Steve Benford et al., 2013). Given that we illustrate our thinking by presenting a set of case studies, our approach also speaks to the idea of a portfolio of design work (B. Gaver & Bowers, 2012). Such an approach has been previously successfully used in HCI when it comes to embodied systems (Andres et al., 2022; Steve Benford et al., 2020; S. Benford et al., 2005; Byrne, Marshall, & Mueller, 2020; Khot, Hjorth, & Mueller, 2020; Mueller, Byrne, Andres, & Patibanda, 2018; Mueller, Dwyer, et al., 2021; Mueller, Gibbs, Vetere, & Edge, 2017; Mueller, Kari, et al., 2018; Mueller, Kari, et al., 2020; Mueller, Matjeka, et al., 2020; Mueller et al., 2014), hence we believe it is also suitable here. Furthermore, we acknowledge the prior work on research-through-design that highlighted that any design work like ours is always required to strike a difficult balance of the needs to appreciate and help develop what is distinctive of design while also build upon design's rich connections to the sciences and humanities (Ghajargar & Bardzell, 2019). Such a balancing act is not always easy to manage, however, in our work, we aimed to achieve a synthesis in the form of a combination of different alternatives rather than favoring one alternative over another. This has been also discussed previously (Ghajargar & Bardzell, 2021), and we believe it can fit quite nicely, especially with our eBike work, as such synthesis was exemplified through bicycle frames (Ghajargar & Bardzell, 2021).

Our results are shaped by our own personal experiences of having designed, developed, used, and studied the first two systems. Our experiences helped us articulate our insights in a practical way. We believe that a deep grounding in our design practice allows to provide immediate value to designers aiming to venture into the field. However, of course, our approach also has limitations, including difficulties with replication. Nevertheless, some of our thinking coming from this practice has been informally validated through a workshop on the topic with over 20 experts from the field (Grudin et al., 2018). In summary, we believe that our design-oriented approach resulted in outcomes that can be a valuable starting point for future design investigations.

5 INTERTWINED FRAMEWORK

The intertwined framework consists of a design space and a set of associated strategies. The design space comes in the form of two dimensions that, together, help articulate the similarities and differences of intertwined systems. This articulation can be useful for designers when they want to explore alternative options for their designs: by moving their existing design along either of the two dimensions, they can identify alternatives, aiding in the process when it is time to determine what to do next. By looking at where in the design space an existing system and an alternative "sits" on the two dimensions, designers can determine what kind of user experience they can anticipate. This can help optimize a particular design undertaking towards a desired outcome.

We are inspired by technological advancements such as smaller, more powerful and more affordable sensors and actuators, but also software advancements like more sophisticated artificial intelligence developments, as we believe that they enable new opportunities to share agency: new sensors and actuators allow for the sharing of agency in an embodied form, enabling new ways to share agency that go beyond cognition-focused screen-based interactions. For example, a user could share agency over their arm with a robotic contraption around their arm, having control over their arm movement most of the time, however, if expert knowledge is required, an expert system could "take over" control of the arm, for example when repairing a complex machine in a maintenance scenario on a factory floor. Here, the hardware enables to guide the user's arm to the right location, while the underlying artificial intelligence system draws from massive amounts of training materials collected from previous maintenance tasks executed by expert workers, supporting the novice worker.

Both dimensions are concerned with the agency of the computational machine. The first dimension captures the extent of human awareness of the computational machine's agency. The second dimension captures the extent to which the machine's agency is aligned with the human's intentions. These dimensions are defined along spectra that run from low to high. This means intertwined systems can be described by a low or high extent of human awareness of the computational machine's agency and a low or high extent of alignment of the machine's agency with the human's intentions. For this, we build on prior work that has suggested that aspects of agency can help us understand integration (Steve Benford et al., 2020), here, we extend it to intertwined systems.

5.1 Awareness of machine's agency

The first dimension is concerned with the extent to which the user is aware of the machine's agency, drawing on prior work on awareness of control in interactive systems (Steve Benford et al., 2020). We refer to agency in our everyday speaking when we say, for example, "It must have been me who just pressed this button" (Braun et al., 2018) or "I did that!" (Bergstrom-Lehtovirta, Coyle, Knibbe, & Hornbæk, 2018). As such, agency refers to "the feeling of generating and controlling actions in order to influence events in the outside world" (Moore & Fletcher, 2012) or shorter: "The experience of initiating and controlling an action" (Braun et al., 2018).

The concept of agency has recently gained attention in HCI (Steve Benford et al., 2020; Berberian, 2019; Bergstrom-Lehtovirta et al., 2018; 2012; 2019; 2014). This attention is driven, in part, by technical advances, in particular around artificial intelligence including machine learning that allows computational machines to exhibit increased autonomy. A system that "takes over a lot of control that would have been in the hands of the user" (Moore, 2016) can be advantageous. A car that senses a potentially dangerous situation and relieves the driver of control to avoid an accident offers one example of this type of system control. However, the user might be upset if the system is only able to minimize the damage. The user might believe that they could have prevented the accident entirely themselves, had they been in control, even if such an outcome was objectively impossible. Consequently, research points to the need to better understand agency, and especially how to design systems in which agency is shared (Moore, 2016). Prior work also highlights the difficulty of such an undertaking, and that complexity only increases as technological advancements enable more sophisticated forms of shared agency (Berberian, 2019). With our work, we enhance our understanding in this regard by providing knowledge on how to design intertwined systems where agency is shared between a computational machine and the user's body.

We agree with prior work that highlights that agency is not a binary construct (Braun et al., 2018), and, as suggested in HCI (Steve Benford et al., 2020), we define it along a spectrum. Specifically, we build on prior work by Benford et al. (2020)

that has proposed awareness as a dimension to understand autonomous systems; here, we argue that a user's awareness of a computational machine's agency is a key dimension for intertwined systems. Furthermore, we propose that designers should consider whether and how to facilitate this awareness, as it can critically influence the resulting user experience. We now describe the dimension of awareness of the computational machine's agency in more detail and discuss its two ends: high and low awareness.

Users can have a high or a low awareness (to the extent that there is no awareness at all) of a computational machine's agency, and this awareness may be anywhere in between the extremes. For example, a user can be made aware (for example, through explicit instructions beforehand) that a system possesses agency to take control over an interaction. However, if the user forgets these instructions, they will have a lower awareness of the computational machine's agency, particularly when that agency is not immediately apparent.

5.2 Alignment of the machine's agency

The second dimension of our framework has to do with the extent to which the computational machine's agency is aligned with the user's intention: the extent to which the computational machine works with or against the user (for example, the degree to which the machine might steer the user in a certain direction). One might expect that the machine should always work with the user. However, in some application domains, such as games, it can be advantageous if the computer serves as an adversary, posing a challenge.

At the high alignment end of the dimension are systems in which the machine's agency is aligned with the user's intention and amplifies the user's abilities. However, due to the human body's many degrees of freedom, these machines are often only crudely aligned as they can only support a limited range of intended movements.

6 THE INTERTWINED DESIGN SPACE

By drawing the awareness and alignment dimensions perpendicular to each other, we construct a design space within which we can position systems and highlight their similarities and differences (Figure 4).

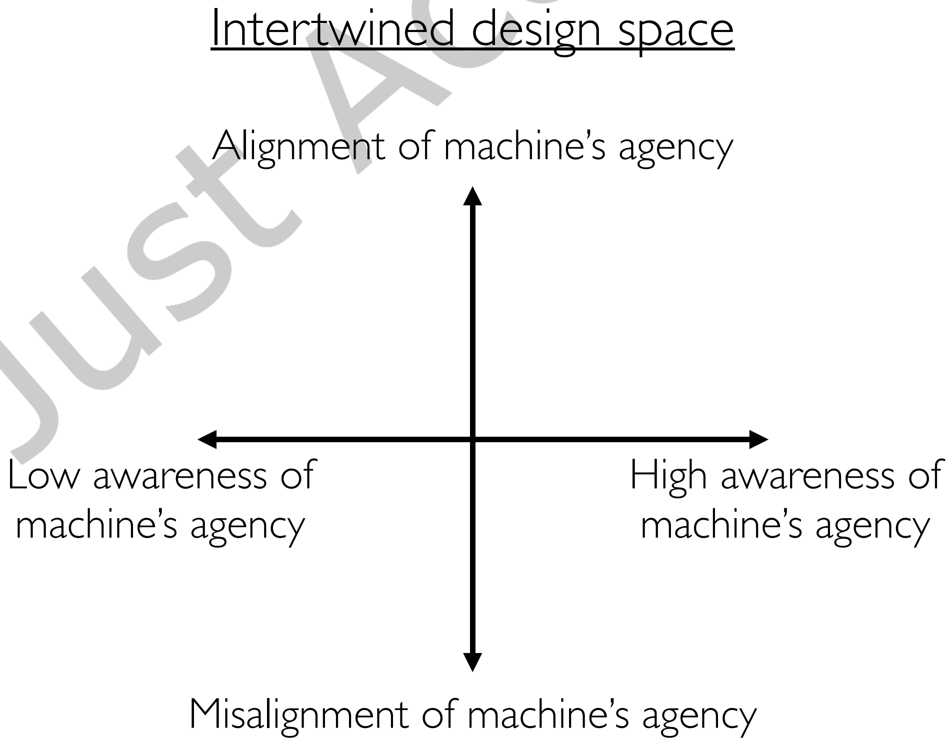

Figure 4. The intertwined design space.

We build on prior work by Mueller et al. that has similarly visualized a design space for bodily systems (2020) and present a two-dimensional design space that encourages future system designers to consider both awareness and alignment. This visualization highlights that designers can aim to facilitate varying degrees of awareness and alignment and that these combinations can drive various user experiences. These different user experiences become apparent when looking at the design space's four quadrants. Furthermore, the design space highlights that "more" of a particular dimension is not always desirable and that "less" can be combined with "more" across different constellations. We also acknowledge that most systems do not necessarily occupy a fixed position in the design space for the entire experience. Indeed, our case studies often follow trajectories (Steve Benford, Giannachi, Koleva, & Rodden, 2009) through the design space, which we describe later.

We acknowledge that this visualization of the design space can only be described as an initial attempt to provide a simplified abstraction of the complex notion of agency. Furthermore, as we are interested in bodily systems, we focus on the different ways agency can be experienced with and in the body and we aim to describe this in our case studies below. We highlight that any alignment of the machine's agency as well as awareness of the machine's agency could be experienced through perceptions, such as through vision and sound, something that interaction designers are usually well versed in through developing systems using displays and speakers. However, any alignment of the machine's agency as well as awareness of the machine's agency could also be experienced, which is possibly more pertinent for bodily intertwined systems, through sensations. Such sensations can be the kinaesthetic sense (the sense of movement), the proprioceptive sense (the sense of limb positions in relation to other limbs), the sense of touch, the sense of smell, etc. (Slatman, 2016), which interaction designers usually do not have that much experience with when it comes to designing for them (Mueller, Byrne, et al., 2018). Therefore, to design for intertwined systems, and in particular for the two dimensions we just proposed, there might be a learning curve required for interaction designers as they might need time to explore how to consider bodily ways to facilitate any alignment and awareness of the machine's agency.

7 FOUR USER EXPERIENCES

The quadrants of the design space help identify key user experiences (Figure 5). Each quadrant involves opportunities and challenges. We list these opportunities and challenges in table form (Table 2) before discussing them in greater detail.

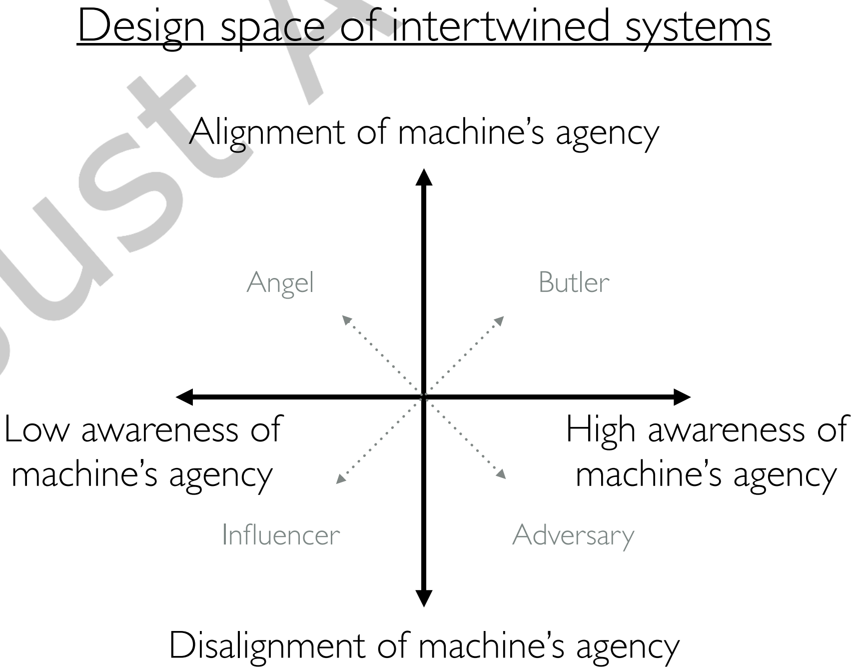

Figure 5. Four roles the system can take.

Table 2. Opportunities and challenges for each role.

Role	*Opportunity*	*Challenge*
Butler	Supporting true collaboration	Possibly condescending with trivial tasks
Angel	Ability to feel like who one wants to be	Dealing with system support ending
Influencer	Facilitating unconsidered experiences	Potential for persuasive misuse
Adversary	Interdependent competitions	Designing for flow

7.1 Upper-right: Butler

The upper-right quadrant of the design space contains systems in which, first, the user has a high awareness of the computational machine's agency, and second, the machine's agency and the user's intentions are aligned. We describe the user experiences associated with these systems as resembling having a butler. The user is aware that the butler executes tasks for them, as the butler was hired for that reason, and the butler fully aligns their actions with the user's intention.

Traditional, engineering-focused support systems fall into this quadrant. A computational machine senses user actions and aims to support the user in their task. System examples include early visions of autonomous cars where the user only has to input their destination, and the care drives them to it, just like a butler would.

7.1.1 Design opportunity

We believe designers can create systems in which computational machines and users truly collaborate and complement each other. While systems already offer turn-taking, intertwined systems present designers with the opportunity to facilitate true collaboration, in which the computational machine seemingly supports the user throughout the process by continually sensing what the user is about to do and anticipating their next move (possibly through the use of machine learning), not unlike a butler who has gotten to know the user intimately over many years.

7.1.2 Design challenge

Given contemporary social norms, we believe that a butler could be perceived as intrusive and perhaps patronizing or condescending, especially where it seems that a task can be easily performed unassisted. This risk might be exacerbated in social contexts where others assume that a butler performs trivial tasks. Charlie Chaplin's Modern Times movie made fun of this assumption with machines working as butlers and supporting seemingly trivial tasks such as eating (which we will come to later in our case study). The same issue applies to intertwined systems. For example, an abled-bodied person is unlikely to wish for, or appreciate, having to wear an exoskeleton that assists them with the trivial task of picking up a small item. As such, we highlight the challenge that such systems can be perceived as condescending.

7.2 Upper-left: Angel

The upper-left quadrant of the design space contains systems in which, first, there is low awareness of the computational machine's agency, and, second, the computational machine's agency and the user's intentions are aligned. We use the term "angel", as the resulting user experiences remind us of having a guardian angel who looks after us in an almost supernatural way.

The computational machine supports the user, enabling them to achieve things that they could not achieve alone (or would find much more difficult). However, unlike the butler, there is little to no awareness of the Angel system's agency. Users can feel that they alone achieve the outcome or that the world is unfolding in their favor.

7.2.1 Design opportunity

Designers can help users experience a better version of themselves. For example, an intertwined integration system could allow people to experience what it would feel like if they were fitter (as an eBike might do) or had lost weight (such as suggested by augmented shoes that play back lighter footstep sounds to the user via headphones) (Tajadura-Jiménez et al., 2015). Another example is intelligent eyewear that makes the wearer believe that they can see non-visible light (Schmidt, 2017). We believe that personal experiences are important (especially compared to imagination or receiving third-person accounts) because users get to live their better selves. These experiences help users figure out who they are and who they want to become (F. Mueller & S. J. Pell, 2016; F. F. Mueller & S. J. Pell, 2016). Bodily systems can support these processes (Mueller & Young, 2017, 2018) and we think that intertwined systems hold the potential to facilitate them due to their focus on bodily experience.

7.2.2 Design challenge

The design challenge with systems in this quadrant is that users could become used to having an angel system available and grow careless. In certain situations, users might not be aware that the angel has become unavailable, and they might choose to engage in what are, without an angel, reckless actions that put them in danger. For example, if a rock-climber uses an angel system that supports their climbing, and the system manufacturer turns off the system without the user's awareness, will the user at that moment be in danger of falling? Additionally, will the user become less confident in future systems supporting them because of this type of bad experience? We agree with prior work that these considerations are important challenges for future work (Mueller, Lopes, et al., 2020).

7.3 Lower-left: Influencer

The lower-left quadrant of the design space contains systems in which, first, there is low awareness of the computational machine's agency, and, second, the computational machine's agency and the user's intentions are misaligned. Such systems often aim to subtly influence the user to change their current behavior in some shape or form. In keeping with this aim, we describe these systems as "influencers". Our description is also inspired by social media influencers (and the associated algorithms that feed their success), who have the power to affect the actions of their followers by seemingly supporting them, even though they are often driven by (and drivers of) external (marketing) objectives that may not be aligned with those of their followers. Systems in this quadrant are analogous with interaction design approaches to "nudging" people toward behavioral change (Kalnikaite, Bird, & Rogers, 2013). For example, some systems subtly guide people toward using stairs instead of an elevator, thereby increasing their physical activity. The system might "nudge" by using small light indicators embedded in the floor rather than a blunt sign at the elevator saying "take the stairs to avoid becoming overweight!" (Rogers, Hazlewood, Marshall, Dalton, & Hertrich, 2010). Similarly, we can envision an "influencer" experience via an intertwined system that gently guides the user towards the stairs and away from the elevator in such a way that the user has low awareness of the computational machine's agency, and the computational machine's agency supports the user's walking actions. An intertwined system using electronic muscle stimulation (EMS) to trigger leg-turning muscle movements that slightly steer a pedestrian in a certain direction – such as the "Cruise Control" system (Pfeiffer, Dunte, Schneegass, Alt, & Rohs, 2015) – could enable such an experience.

7.3.1 Design opportunity

Opportunities exist, including and beyond the stair example above, to facilitate novel and unintended user experiences. While the stair-related system addresses an instrumental goal, systems could also support experiential goals. For example, the above mentioned EMS system for pedestrians (Pfeiffer et al., 2015) could be used to guide people in the right direction if they are lost (instrumental), but it could also guide people around alternative routes that might be more awe-inspiring (S. Lopes, Lima, & Silva, 2020; Mueller et al., 2022) as part of a daily walk (experiential). In this case, the "influencer" experience influences the user toward a behavior they did not initially intend but nevertheless positively benefit from.

7.3.2 Design challenge

The name "influencer" already hints at the key challenge for systems in this quadrant. Influencer systems could be misused in ways that are not in the user's best interests. For example, corporations could use such systems to steer people into shops to encourage them to buy products. These systems would "influence" the user to take a specific route that may superficially seem advantageous to the user, but benefits the corporation behind the technology. However, the distinction between who benefits from the influence of the system is not always clear, as relationships of mutualistic benefit also have the potential to emerge (e.g., an "influenced" visit to a shop could serendipitously lead to a positive experience for the user). Therefore, the complexity of interactions offered by such systems gives rise to ethically multifaceted design challenges.

7.4 Lower-right: Adversary

The lower-right hand quadrant of the design space contains systems in which, first, the user has a high awareness of the computational machine's agency, and, second, the computational machine's agency and the user's intentions are misaligned. We call the associated user experiences "adversary" to highlight their competitive characteristics. At first sight, we might not think that systems could be desirable that act as adversaries as they seem to compete with the user. However, we point out that the games field has a rich and well-appreciated history of computers serving as adversaries. In keeping with these possibilities, we highlight that there is potential for intertwined systems to serve as adversaries and for users to enjoy engaging experiences in which they match their bodily abilities against a computational machine.

7.4.1 Design opportunity

Intertwined systems' abilities to provide input and output offer a unique opportunity in this quadrant of the design space. Systems can facilitate "interdependent" (Mueller et al., 2017) bodily experiences, in which the actions of the user depend on the actions of the computational machine and vice versa (Mueller et al., 2017). These interdependent bodily experiences can be richer than the conventional "parallel" (Mueller et al., 2017) experiences where the results are only compared at the end, after user and machine have completed taking their turns. An example of such a "parallel" activity is jogging, whereas boxing is an example of an "interdependent" activity (Mueller et al., 2017).

7.4.2 Design challenge

The design challenge in this quadrant involves the interplay between input and output. The user should have an experience in which they are neither over-powered nor under-challenged. This challenge could be addressed, for example, by using sensors that constantly check with the user if they are in this "sweet spot". Achieving this balance could facilitate desirable and engaging "flow" (Csikszentmihalyi, 1990) experiences for users as a result of bodily interplay (Jackson & Csikszentmihalyi, 1999). However, there exists a limited understanding of the difficult task of predicting user actions (although artificial intelligence has made significant progress in supporting this in recent years)_so that a system can maintain the user's sweet spot experience.

8 SITUATING CASE STUDIES IN THE DESIGN SPACE

We now situate our case studies in the design space and explain how it assists with articulating the associated user experiences (Figure 6). We also explain how the design space can help extend on the design of our case studies. As such, we demonstrate the strength and potential of our design space based on prior work that proposed that a good design space for post-WIMP interactions should exhibit the following features (Beaudouin-Lafon, 2000): it should be "descriptive, incorporating both existing and new applications" (which we demonstrate through using the design space to describe a commercial as well as our own case studies); it should be "comparative, providing metrics for comparing alternative designs" (as opposed to prescriptive, deciding a priori what is good and what is bad) (which we, albeit to a limited extent, do when comparing our three case studies to alternative systems using the vocabulary afforded by the design space's two dimensions); and "generative, facilitating creation of new interaction techniques" (which we do by envisioning alternative designs of the three case studies using the four quadrant names).

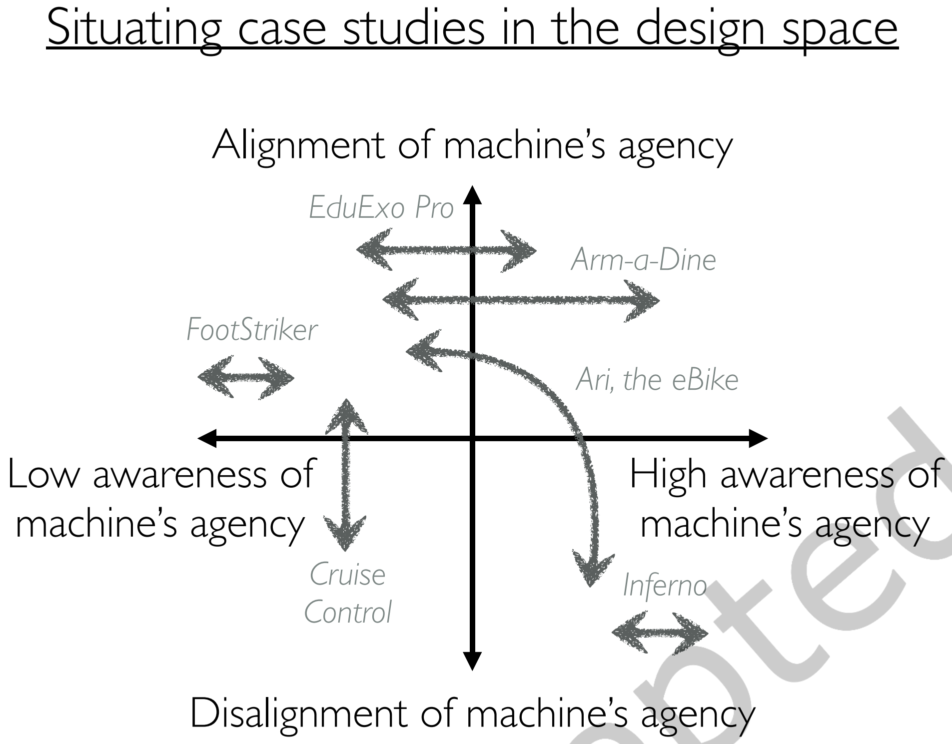

Figure 6. Situating our case studies (and additional systems) in the design space.

8.1 Case study 1: Ari

Initially, the rider has only limited awareness of the eBike's agency. While we informed participants about the eBike's functionality, it was difficult for them to anticipate when the engine would kick in and to what extent. Unlike with a regular eBike that is controlled via a throttle, where the experience is more akin to having a butler that responds to every command from the user, our participants were initially anxious about how the prototype's agency would unfold. Participants reported that although they became more comfortable during the first short distances, they were often not sure if the engine support had already activated. However, the point came when the engine's contribution to the experience was getting so great that participants noticed and reported that they encountered the bike "taking over". This was not facilitated through a display (as often attached to an eBike's handlebar), but riders felt the wind on their skin, and they saw the world around them speed up. They also perceived these changes kinesthetically, via their sense of movement. With an increased bodily awareness of the eBike's agency, the participants felt their system separated from their exertion activity and began "driving them". The system began moving into the angel quadrant, magically supporting the user. However, when engine support increased too much and was no longer subtle, the system moved into the butler quadrant.

Participants also noted that the eBike's "desire" to pass the traffic lights at green sometimes was not aligned with their intention. For example, when the rider's desire for safety superseded their desire to reach the traffic lights when green. Participants explained that there were situations where they had to be more careful than usual – around parked cars opening doors and pedestrians on the road. In these situations, riders reported that they would have preferred to have the power to prioritize safety over system support. Their experience moved into the adversary quadrant in these situations: the eBike provided engine support while the participants used their brakes to react against it.

8.1.1 *Extending Ari through the design space*

The adversary quadrant inspired us to consider how Ari could be used to help people achieve their fitness goals. For example, the system could, first, use a rider's smartphone route planning information to estimate how much effort they are about to invest when riding a specified route. The system could, then, take into account the participant's training plan, using an associated app, and calculate how much extra effort is needed to help the user achieve their goal (assuming that conventional cycling the planned route will not require sufficient amount of effort). Responding to this effort gap, the system then makes it harder, rather than easier, for the rider to pedal. For example, the system could use the eBike's engine as a transformer to charge the battery, which would demand additional pedaling effort. This change in the rider's experience could be extended by making them more aware of the machine's agency. For example, a visual dial showing how much energy the rider's pedaling effort is inputting into the battery, contributing "back" to the system, might raise awareness.

The design space enables to envision alternative designs of future eBikes. For example, we can envision a modified eBike that would not sit in the "butler" quadrant, but rather be situated in the "influencer" quadrant. This alternative version of Ari would be networked with other eBikes and communicate with the local traffic authority. By knowing where all the bikes are, the local traffic authority could adjust their speed and the traffic light patterns so that the bikes are sped up (or not) in a way that they more easily "spread out" across the city, avoiding congestion at busy intersections.

We could also increase awareness of the eBike's agency, moving the associated experience more to the right. For example, our participants reported that when their eBike increased engine support, they would accelerate and leave fellow riders behind. If this gap persisted, the quality of the rider's social interactions would be poorer. While a rider might choose to verbally alert their fellow riders that they were accelerating, we can imagine a technical solution to make others more aware of the machine's agency: an embedded display in the helmet (Walmink, Chatham, & Mueller, 2013; Walmink, Wilde, & Mueller, 2013) or speakers attached to the bike (Andres et al., 2019).

8.2 Case study 2: Arm-A-Dine

Participants of the Arm-A-Dine system appeared to have had an intertwined experience as they controlled the additional arm with their body, using their own body movement and their facial expressions, while the additional arm (at least partially) controlled what food they (and their partner) ate.

People who used the Arm-A-Dine system quickly became aware that the robotic arm mostly controls itself. The arm moves its individual joints autonomously, albeit in a rather predictable pattern. Consequently, users who are aware of these patterns are able to quickly incorporate them into their own bodily activities and align their own body position so that the arm picks up the right food and presents it directly in front of the other person's mouth, not unlike when dining partners feed each other. Based on these observations, we note that there appeared to be an awareness of the computational machine's agency. Participants could experience the system as a butler and work together to achieve the desired outcome of eating together. However, participants found it more difficult to use the robotic arm than their own arms. The robotic arm's fidelity is far inferior to human arms, and, consequently, its movement often worked slightly against the user's intention. For example, the robotic arm usually has trouble stopping completely after moving in a certain direction, and it can "swing" a little further. This made it hard for participants to execute precise movements. However, although such misalignment of the machine's agency was not productive in an instrumental sense, making feeding more challenging, it contributed greatly to the quirkiness of the experience, resulting in a lot of laughter.

Participants also experienced intertwined integration via their facial expression control. First, participants had little awareness that they could play a role in controlling the third arm, although we briefed them about this possibility. Most participants serendipitously realized that their facial expressions – when they smiled after eating a tasty food item or laughed when their partner said something funny – were informing the robotic arm's movement. When they realized that they had shared control over the robotic arm, participants began to explore their agency, trying various facial expressions to see which ones produced a system response. In these situations, the system moved from the angel quadrant – seemingly autonomously supporting feeding (like an angel feeding a hungry beggar) – to an experience in which the user commands a butler to feed one another.

8.2.1 Extending Arm-A-Dine through the design space

We used the design space to explore how we might increase awareness. For example, we could have implemented a screen showing which of the diners' facial expressions are recognized. While this awareness might allow for more effective control of the robotic arm, it might also reduce the ambiguity (the playful suspense of who was going to be fed next) that participants appeared to appreciate. We contend that our work brings together two research pathways, concerned with the value of ambiguity for playful interactions (W. W. Gaver, Beaver, & Benford, 2003) and the role of ambiguity in the sense of agency (Gallagher, 2013) respectively.

We also used the design space to envision a version of the Arm-A-Dine system that functions as an influencer for healthier eating. We can imagine the system subtly steering the robotic arm towards healthier food or modifying the gripper to pick up smaller portions. If the user has low awareness of the machine's choices, they might simply attribute them to chance and eat more healthily. Such an influencer system raises interesting ethical questions, including those to do with user's agency over what and how much they eat and their freedom of choice. For this, we point to prior work around ethical issues associated with eating interventions that facilitate low awareness of the system's agency (Adams et al., 2015).

Furthermore, we can also imagine that a misalignment might be beneficial when it comes to supporting safety aspects. For example, a system might sense that the user is getting themselves into a dangerous situation as a result of their actions, and, in consequence, would work deliberately against the user's intention as a way to reduce the risk, ensuring safety. For example, a riding-support system might sense that the user is cycling very close to a waterway ledge, maybe not aware of wet ground that poses a slipping hazard. The system, in response, subtly steers the user away from the ledge, ensuring safety (for example, through electrical muscle stimulation attached to the user's arms to control the steering (Pfeiffer et al., 2015)).

8.3 Case study 3: Exoskeleton

We believe that the experience of using Auxivo's exoskeleton sits in the upper left of the design space, the Angel quadrant. The wearer usually has a low awareness of the machine's agency, as the system is designed to not impede with their movement and support the user in a rather concealed way. For example, the exoskeleton could be worn underneath clothing. However, as prior work pointed out (P. Lopes & Baudisch, 2017), most exoskeletons are still rather large and would not fit easily under clothing, and if they do, protrude quite extensively. Furthermore, users would need to go through a tailoring phase first, and then through an attachment process every time they decide to wear the system. This would increase their awareness of the machine's agency. This awareness is increased further through the noise the motors make whenever the system provides support. Additionally, the wearer experiences a tactile sensation on their skin when the pads of the exoskeleton push their arm up when providing support. As such, we position the exoskeleton on the "low awareness" end of the dimension, but not as far left as some of the other systems. Furthermore, we postulate that with extended use, wearers will become faster with the attachment process and more familiar with the pads' tactile sensations, moving their initial "reflective awareness" to a "pre-reflective awareness" where the user is not constantly judging their body and the computational machine to coordinate the movement but is rather able to focus their conscious awareness on other tasks, such as holding a conversation (Danry et al., 2022). When it comes to the "alignment" dimension, we propose that the exoskeleton sits towards the "top" end of it. This is because the included EMG sensor is designed in a way to detect a movement very early on, so that the machine can become aware of the user's movement intention and support it. In other words, the computational machine aims to support the user in their intention to move a certain way. However, we note that the system can, in certain situations, also work against the user's intention: the exoskeleton's mechanical construction and size can also work against some movements the user might want to perform. For example, the user might want to twist their arm in a certain way, for example when aiming to retrieve objects in small spaces. Through the size of the exoskeleton and the mechanical construction constraints, these movements can be harder to perform than without the exoskeleton, hence the user might be advised to remove the system beforehand. This, in turn, will reduce the chances to incorporate the device into the user's body schema, as such an incorporation process can benefit from long-term engagement (Carlson, Alvarez, Wu, & Verstraten, 2010; De Vignemont, 2010; Gallagher, 1986; Pitron & de Vignemont, 2017). This is further hindered by the fact that the user will probably need to take off the device every time when exchanging empty batteries.

8.3.1 *Extending the exoskeleton through the design space*

We can use the design space to envision alternative versions of the exoskeleton. These can probably be easily implemented through the modular design of the system. For example, we can envision moving the system "down" on the disalignment dimension where the system works deliberately against the user's intention. This could be easily achieved by inverting the direction of the motor when the EMG sensors detect muscle activation: so instead of the motor easing the lifting of objects, the motor would make lifting harder. By keeping the awareness low, the system could function as a subtle influencer, covertly aiming to help the user train their muscles when lifting everyday objects. Such a system could be useful for hidden strength training in rehabilitation or for sports. By moving the system also to the right, making the user more aware of the system working against their intention, we result in the "adversary" quadrant. Such a system could be useful in an entertainment context where the user's movements are counter-acted upon, promoting ultimately that the user does not move much. This could be a playful approach to common mind-body practices like meditation that promote non-moving.

We can also envision moving the system more to the right of the awareness dimension by, for example, attaching LEDs that make the user more aware when they are receiving lifting support. Furthermore, we could also envision installing speakers that make the user more aware when they are getting support by the exoskeleton, allowing to reach the user even if they are not looking at the LEDs. Such increase of awareness would also make bystanders more aware that there is a system in place that supports the wearer. This could be beneficial, for example, for judges in sports competitions, where they need to assess the athletic prowess of a competitor; this would allow them to see if and when an exoskeleton supports the wearer's efforts. As such, we end up in the "butler" quadrant, where the system supports the user in their intention in a way that is clearly visible to the wearer (and any bystanders).

8.4 Additional systems

To demonstrate the strength of our design space further, we now articulate how the design space can be used with other intertwined systems. This is again based on prior work by Beaudouin-Lafon who argued that a design space should be descriptive, comparative and generative (Beaudouin-Lafon, 2004). As such, we see this articulation as complementing our above case studies that demonstrate the descriptive, comparative and generative power of our design space.

FootStriker (Hassan et al., 2017) is a system developed for runners. It uses electrical muscle stimulation and an insole with force sensing resistors to detect heel striking in order to actuate the calf muscles during the flight phase to control the foot angle before landing. This aims to support a more efficient running style through promoting mid- or forefront running compared to striking the ground with the heel first. We propose that this system sits across the influencer and angel quadrant of the design space, as the user generally has a low awareness of the machine's agency. The jogger knows what the system is aiming to achieve (assuming that they are using it to improve their running style), however, especially during long-distance runs, the jogger's awareness might shift away from focusing on their calf muscles (this shifting is one of the reasons why simply "telling oneself" to shift to mid- or forefront running is often hard to achieve). In terms of the position on the y-axis, we believe that FootStriker sits in the upper half, as the computational machine's agency is aligned with the jogger's intent, that is, improving their running style. The experience for the user is one as if there is an angel that places their food mid- or forefront through sheer "magic". However, if the system was prescribed by a coach, we can also see how the system features characteristics of an "influencer", as the jogger is influenced to run in a certain way. The design space helps to articulate the comparison with an exoskeleton that might be designed with the same goals: as an exoskeleton is usually much more visible to the user (and heavier, adding a tactile component) and any bystanders, the awareness of the machine's agency would be much higher, situating the exoskeleton system more in the "butler" quadrant of the design space.

The system "Cruise Control" uses electrical muscle stimulation on the sartorius muscle to influence walking direction in pedestrians (Pfeiffer et al., 2015). The actuation is triggered during the swing phase of the leg. We would position this system in the left hand of the design space as the user generally has a low awareness of the machine's agency. As the user is already moving their leg, the electrical muscle stimulation is not as much felt as if the legs would be resting. As the original system is intended to steer the user in a certain direction without their knowledge, we would say that there could be a disalignment between the user and the machine's agency, for example if the user wants to go into a different direction to the system. However, we could also envision a situation where the user just wants to go for a walk, and the system makes direction suggestions, therefore exhibiting more of an alignment with the user's intention. As such, we place the system possibly moving between the angel and influencer quadrant.

"Inferno" is an art performance in which large exoskeletons control the upper limbs of volunteers controlled by a DJ, who makes them dance to the music, set within a dystopian environment (Diitalarti, 2016; Meta.Morf, 2018). Here, the exoskeletons are not controlled by the wearer, but another person (the DJ), hence we postulate that for most of the time, there is a high disalignment between the user's intention and the machine's agency for the sake of an intriguing spectacle for the audience. As the exoskeletons are oversized to support the dramatic effect of the performance, it is quite obvious for the wearer (and the audience) that they are controlling the user, hence we can say that there is a high awareness of the machine's agency. Therefore, Inferno sits in the adversary quadrant of the design space.

9 DESIGN STRATEGIES FOR INTERTWINED SYSTEMS

We now use our knowledge and experiences to articulate practical strategies for designers (especially those new to the field) when navigating the intertwined design space. We complemented our craft knowledge, gained through designing our systems, with insights from our associated studies, particularly, from those instances in which the systems worked, and did not work, for our participants.

We arrived at our proposed strategies as part of our research-through-design process (Dow et al., 2013; W. Gaver, 2012; Zimmerman et al., 2007), during which theoretical thinking, together with looking at the literature, was interspersed with design activity and complemented by reflections upon our knowledge and our knowledge gaps. The process did not follow a pre-described approach as we did not design our systems with the aim to create an intertwined framework article, but rather, it organically emerged as part of the entire project's duration. This is beneficial, we believe, in terms of applicability to industry, as we are able to report insights derived from the trenches, however, we acknowledge that this of course also has limitations, such as concerning replicability. Nevertheless, we believe that our strategies have value as they offer the first articulation of insights directly applicable to designers and hence hopefully serve as valuable springboard for future work. We also point out that this process' messiness is characteristic of design research (with all its advantages and disadvantages) and has been reported in prior work (Mueller, Byrne, et al., 2018; Mueller, Matjeka, et al., 2020; Mueller et al., 2014).

As part of this process, we found it useful to conduct a lot of thinking through writing, where we referenced our prior work on bodily experiences and tried to articulate what we have learned by abstracting our designs to higher-level language (Mueller, Matjeka, et al., 2020). Large parts of the final writing were done on a (limited) intertwined system – a powered home trainer bike connected to an app that uses elevation data of famous cycling tracks worldwide to adjust the pedal effort required by the bike, speaking to our dimension of (mis)alignment between the bike and the cycling author. As such, thinking was facilitated through bodily activity, which complements our argument in the paper quite nicely, we believe.

We present the strategies in no particular order. Designers should begin with those strategies most relevant to their context. We claim neither that the implementation of all strategies leads to success, nor that all strategies must be considered. Furthermore, we highlight that this set of strategies is not a complete list, but rather a starting point that designers might find helpful, especially if they are just starting out. We acknowledge that some cover the embodied nature of our designs only to various extents and hence encourage future work around refining and complementing them. We propose that designers use them as starting points to learn from our past experiences, to avoid pitfalls. Furthermore, we point out that educators could use the strategies for their students as practical guidance for their class projects on intertwined systems. Ultimately, we hope our strategies are useful for others in their design practice, following prior work that presented strategies in interaction design research papers (Steve Benford et al., 2012; Marshall et al., 2011; Mueller, Byrne, et al., 2018; Mueller, Kari, et al., 2018; Mueller, Matjeka, et al., 2020).

We begin with a summary of the design strategies (Table 3).

Table 3. Design strategies for intertwined systems

Strategy title	*Strategy considerations*
9.1 Ethics	Consider addressing the ethical implications of low awareness of the machine's agency
9.2 Sharing	Consider sharing awareness of the machine's agency
9.3 Reflection	Consider supporting reflection on user's agency
9.4 Differences	Consider accommodating bodily differences when tuning the alignment
9.5 Safety	Consider offering the opportunity to regain control at any time
9.7 Connectedness	Consider distributing alignment for social connectedness

9.1 Ethics: Consider addressing the ethical implications of low awareness of the machine's agency

We have outlined that facilitating low awareness can have many benefits, including allowing users to engage in experiences they might not otherwise have tried. However, we highlight that designers of systems in the angel and influencer quadrants should carefully examine how to ethically implement low awareness of the machine's agency, as the embodied nature of intertwined systems poses additional challenges to designers compared with more traditional systems that also exhibit agency, but in a less embodied form, such as chatbots.

Users who have a high awareness of the machine's agency can probably make more informed decisions on consenting to machine support (yet there are still ethical concerns such as potential overreliance on the support, which can be troublesome during machine failure) compared to users with low awareness. If the user is only aware to a limited extent (or not at all), questions arise about whether users attribute their seemingly new abilities just to their own body, that is, themselves, which, over time, could lead to a skewed self-image. Such a skewed self-image can result in significant detrimental health effects, which designers of traditional systems might not immediately think of (De Vignemont, 2010; Gallagher, 1986; Pitron, Alsmith, & de Vignemont, 2018). How to consider the user's consent in this is an important part of future research, we believe. Overall, we extend prior work on ethical implications of embodied designs (Strengers, Sadowski, Li, Shimshak, & Mueller, 2021) by highlighting that when it comes to intertwined systems, designers should, in particular, consider any low awareness of the machine's agency due to the intertwined involvement of the human body in the associated experiences as it can lead to skewed self-image.

In our work, we have worked extensively with our ethics committees during our practice and found that engaging early with ethics questions is one way to facilitate a trusting relationship that can carry over to the relationship with the participants. We also note that we experienced that a balance needed to be found. On the one hand, telling participants of the machine's agency assists with gaining informed consent. On the other hand, we wanted to give participants minimal instructions to allow them to explore how the system could work best for them without preconceptions. As such, there is a conflict between making users aware that they are supported by a machine, moving the experience to the right of the design space, or aiming to the left of the design space, which comes with a reduced awareness that can raise issues around consent. For this, we found it helpful to look at what our medical colleagues previously did, as considering such ethical issues in terms of bodily experiences has a richer history there compared to HCI.

We believe that the experiences discussed in this paper highlight the potential of intertwined integration, especially when it comes to the eBike. Our eBike participants reported that they felt that it was "them" who held the ability to go fast, rather than a system speeding them up. Nevertheless, we stress the importance of considering what this means ethically for our perception of ourselves, as previously highlighted in related work (Mueller, Lopes, et al., 2020).

9.2 Sharing: Consider sharing awareness of the machine's agency

We recommend that designers consider sharing awareness of the machine's agency with others to support the social aspect of intertwined integration. The design of embodied systems benefits from considering social aspects due to, in part, the visibility of the body's actions to others, as previous research in embodied interaction highlighted (Hornecker & Buur, 2006; Klemmer & Hartmann, 2006), The same applies to intertwined systems, we find. We extend this prior work by suggesting to consider this social aspect in particular in regard to the opportunity to share awareness of the machine's agency. Let us explain: Most designers have experience with sound or visual feedback. Therefore, we believe that designers have the opportunity to easily use interactive technologies, including sound and lights or displays, that can often be readily implemented at low cost, as a way to support sharing awareness. By sharing awareness with others, for example through a large highly visible display, others can be informed of the machine's agency, and possibly even inform the user of aspects of the agency they might have missed themselves, resulting in increased awareness of the machine's agency, which is often desirable. How to do this best considering the embodied nature of the systems is still an open question for future research to explore. However, we can point to emerging work around wearable displays and displays on the skin that might be useful to consider when aiming to share awareness of the machine's agency in intertwined systems (Bergstrom-Lehtovirta et al., 2018; Kao, Holz, Roseway, Calvo, & Schmandt, 2016; Mauriello, Gubbels, & Froehlich, 2014; Page & Moere, 2007). With our work, we extend prior work on awareness (Steve Benford et al., 2020; Ciochetto & Haley; Jonsson et al., 2016; Lindley & Monk, 2008; Rettie, 2003) by highlighting that interaction design also has potential to support awareness in intertwined systems; in particular, designers should consider using interactive means to support awareness of the machine's agency due to the visibility of the user's bodily actions (and the system) during these intertwined experiences.

In our eBike study, we found that informing fellow riders that an eBike is about to accelerate could be beneficial as it helped prevent them from falling behind. As previously suggested, increasing awareness could be easily achieved through, for example, a speaker on the bike's handlebar that plays a sound to represent the increase in speed (Andres et al., 2018). Indeed, commercial eBikes are already experimenting with introducing digital sounds for their bike bells (Vanmoof, 2020). Given that the eBike already has a battery, these changes should be easy to implement. Furthermore, considering that most contemporary riders attach their mobile phone to their handlebar, we also imagine using the phone display to share information about the eBike's agency with nearby others. For example, close-range technologies, such as Bluetooth, could be used to broadcast information to other handlebar-mounted mobile phones nearby.

We considered whether we should "dress up" the Arm-A-Dine robotic arm component, which could reduce others' awareness of its agency. On the one hand, concealing the arm's mechanical components would result in a stronger visual alignment with the eating scenario by improving the overall aesthetic. On the other hand, concealment would probably result in bystanders having less awareness of the robotic arm's agency. Ultimately, we decided to leave the robotic arm highly visible to stress its agency to others. This visibility led to people talking about the arm's functioning during the interviews.

The enhanced ability of the exoskeleton's wearer could be shared with others, for example, through LEDs attached to the outside of the user's garments. This might help make co-workers, who are not wearing such a device, be aware that they are not required to perform at the same level as the exoskeleton wearer, limiting the chances of overworking and hence potential for injury in more competitive-inclined workers.

9.3 Reflection: Consider supporting reflection on user's agency

When using intertwined systems, it can be difficult to determine and differentiate the relative contributions of the user and the machine to the experience. We contend that this indeterminacy offers designers an opportunity to support users to reflect upon their own agency and, more generally, to help them think about the extent to which they have control over certain aspects of their body and hence their actions. Where the system uses ambiguous data, such as biodata, these reflective opportunities are richer, as prior research suggests (Isbister, Höök, Sharp, & Laaksolahti, 2006). Hence, we believe that the embodied nature of intertwined systems supports reflection in enriched ways, in particular in regard to their own body and any associated health implications, compared with, for example, afforded by traditional interactive systems (Fleck & Fitzpatrick, 2010; Ghajargar & Wiberg, 2018; Hallnäs & Redström, 2001; Jung, 2020; Kozubaev et al., 2020). As such, we extend prior work on reflection (Fleck & Fitzpatrick, 2010; Ghajargar & Wiberg, 2018; Jung, 2020; Kozubaev et al., 2020) by confirming the opportunity to support reflection through interactive designs and add that intertwined systems seem to be particularly useful when it comes to supporting reflection around the user's bodily actions and hence their own self. However, we leave experimental studies to confirm this for future work.

For example, in our eBike work, we used interview questions to facilitate participant reflections on agency. Participants reflected upon how our eBike changed their perceptions of agency in regard to their own body, compared to their previous experiences riding their own eBikes. Participants also compared their effort and contribution when riding conventional bikes with cycling on the eBike – which contributes via its engine – and they reflected upon what this difference meant for their fitness. We note that such discussions about whether eBike's are beneficial or detrimental to a rider's fitness are not new, with research suggesting that eBikes make a positive contribution to physical health (Johnson & Rose, 2015).

In our Arm-A-Dine work, we also used interviews to explore agency questions. However, we acknowledge that participant reflections did not offer as many substantive insights into agency as our other work. Nevertheless, participants discussed how much control they had over their eating: what they ate, how much, and, more particularly, how others around them influenced their eating. How much control people have over their eating, and the roles that other people, and external factors such as the environment (Hillier, 2008) play in eating behaviors, are fascinating and widely researched topics in a society that hopes to tackle contemporary obesity problems (Jiang, King, & Prinyawiwatkul, 2014; Thompson, 2004).

Designers of future exoskeletons could consider how they support reflection on the user's agency when carrying heavy objects. Assuming that the system is worn by full-time workers over many years of labor service, the impact such a system could have on the perception of their lifting abilities and in consequence their bodily abilities more generally and hence their sense of self is high if we compare it to the use of the system as a one-off during a small experiment as part of a research lab study. As such, workers might benefit from being supported to reflect on the use of the system and how it affects their own image of being a laborer. This could include facilitating reflections by others on how they see such a worker's job and hence the worker. With the seemingly increase of exoskeletons in the workplace ("Exoskeleton report," 2017; Grand View Research, 2018), this could be an interesting avenue for future work, potentially resulting in significant outcomes for industry and how to support laborers in the long term.

9.4 Differences: Consider accommodating bodily differences when tuning the alignment

We suggest that it is important to consider people's bodily differences when designing the alignment (or misalignment) of the machine's agency with the user's intention. Aligning people's different bodies with a computational machine is often a complex process that requires personal tailoring. While this requirement can add to the time and cost of system development, it can also support more personalized and consequently hopefully improved experiences. With this strategy, we confirm prior theory around human-computer integration that suggested to not forget bodily differences when designing such systems (Mueller, Lopes, et al., 2020). We also extend this theory by adding that designers should consider accommodating these bodily differences in intertwined systems, in particular, the tuning of the alignment is important here as the machine's agency is often tightly intertwined with physical components that can directly interfere with the user's body.

We made sure that eBike participants could adjust the seat to their preferred height, ensuring a good compromise between comfortable and an effective riding position, which is key to any riding experience. However, there are many more parameters that can help align a bike with a user's body, including handlebar height, frame size, wheel diameter, and gear ratio. In interviews, participants discussed how the individual adjustments and customizations they implemented on their own eBikes made their riding experiences more personal, and that they missed these personalized features when riding our prototype. This difference was exacerbated by the eBike's agency. When accelerating to make the next set of lights, the more comfortable participants were with the bike in general, the more comfortable they appeared to be with the acceleration. Participants reported that they felt more at ease for the eBike to take control if they had confidence in their ability to control the bike. For example, they reflected that they could quickly grab the brake levers on their own bikes without a conscious effort because, unlike on the eBike, they were familiar with the form, shape and location of those brake levers.

Arm-A-Dine participants wore a vest to which the robotic arm was attached. We chose a Taekwondo vest as it provided a good balance between wearability and sturdiness for mounting the arm. However, because this mount was a permanent fixture, we could not change to different vest sizes for different people's body shapes and sizes, which would have been preferable with the benefit of hindsight. With a better-fitting vest, some participants could have had more agency over the robotic arm, which might have changed how they engaged with any shared control. It appears that the one-size-fits-all vest moved slightly on the body, making it more difficult for participants to aim. As such, we highlight the need to consider bodily differences to create a tighter coupling. Also, loose coupling can make it hard to identify whether the looseness or the machine is responsible for a particular action, which introduces unnecessary ambiguity.

The exoskeleton system also benefits from the consideration of different body types. Hence, most exoskeletons come in the traditional S, M, L sizes. Although body sizes vary more, these three standard sizes are often a compromise between accommodating different people yet keeping costs down, as development not only costs time but also money, not to mention storage. For example, in our research lab, we often want to have multiple sizes of our wearable systems readily available for visitors to try, however, often find it challenging to develop, resource, and store many different sizes.

Of course, tailoring systems to individual bodies is not new and has been discussed in relation to wearables and fashion. Furthermore, prior work has highlighted how people with disabilities might require personal tailoring but should not be left out when it comes to integration systems (Mueller, Lopes, et al., 2021). Here, we extend this prior work on tailoring to highlight that designers of intertwined systems should not only consider accommodating bodily differences but pay particular attention in regard to the tuning of the alignment as the machine's agency is often tightly intertwined with physical components that can directly interfere with the user's body.

9.5 Safety: Consider offering the opportunity to regain control at any time

Safety is an important aspect of any intertwined system. As the system has the ability to act with autonomy, and especially as this autonomy can occur in bodily form, there is a risk that users could be physically harmed. This risk can be increased by more powerful systems, such as those with actuators that can act on the human body. Consequently, designers need to pay particular attention to ensure safety.

Because our eBike's engine is rather powerful, we paid great attention to safety. We put sensors on the brakes so that any engine support would stop as soon as users operated them. However, we discovered that this solution was not elegant. The slightest braking pressure produced a noticeable "jerking".

Because the Arm-A-Dine robotic arm operated close to people, we programmed it to not move too quickly. While we considered a stop button, we found the slow movement was sufficient to prevent any harm. Also, because the arm was mounted on the body, the user could always move their torso in order to compensate for any unintended robotic action; they could make larger movements to cancel out the robot's smaller movements.

The exoskeleton appears to offer wearers the opportunity to regain control at any time through the easily removing of the power cable. The placement of this cable is an important design consideration, as it must be reachable with ease, even when already under stress, such as when lifting heavy objects.

Safety is a design imperative for intertwined systems, and the user's ability to regain agency is a particularly important consideration. Designers should also consider how to make it easy for participants to engage with the safety features offered. Prior work has already highlighted that integration systems might limit a user's bodily actions, potentially preventing them from pressing a stop button. Given this risk, we should consider other input possibilities, such as verbal commands (Mueller, Lopes, et al., 2021). As such, we confirm this prior theory that users should be given the opportunity to regain control at any time also in intertwined systems.

9.6 Connectedness: Consider distributing alignment for social connectedness

We contend that connecting intertwined systems holds the potential to support social connectedness (Van Bel, Smolders, IJsselsteijn, & de Kort, 2009). Networking advances allow to connect intertwined systems, and this ability to connect is valuable to designers. In particular, contemporary wireless technology allows to easily connect both physically proximate and physically distant intertwined systems and people. We also note that latency is no longer likely to be a significant constraint on simultaneous input and output for networked intertwined systems (unlike earlier work on networked bodily experiences found (Mueller et al., 2003)).

The feeling of being connected to others is important for wellbeing (Robinson et al., 2020). Sports teaches us that social connectedness can be an important driver of wellbeing, and prior work has examined how embodied experiences can support participants' social connectedness, even when they are geographically separated (Mueller et al., 2003). In fact, embodied interfaces can facilitate increased levels of connectedness compared to traditional keyboard interfaces (Mueller et al., 2003), even when those interfaces are less intuitive (Robinson et al., 2020). As such, we believe that the networking of intertwined systems carries great potential to support users' social connectedness. We therefore confirm prior theory that distribution via network means holds great potential for social connectedness (Mueller et al., 2003) and stress that the same can apply for intertwined systems.

We have noted that cyclists can enjoy cycling with other eBike riders, but if one of them uses the Ari system, fellow riders might have difficulty keeping up when the eBike unexpectedly accelerates. By wirelessly connecting the bikes, it seems feasible to imagine the bikes sharing location and speed information to help social cyclists stay together. Most cyclists already use cycling apps that track data such as speed and location and upload it to the cloud. Given the availability of this technology and its broad use, it seems that the collection and distribution of such data between the two cyclists or among a group would be quite straightforward. In this regard, a challenge would be how to subtly align the machine's agency with other systems to support the cyclists staying together, while retaining their option to challenge one another.

Furthermore, the rhythmic leg actions of cycling inspired us to speculate about a particular opportunity for intertwined systems to support synchrony, which appears to be a key driver of social connectedness. Prior work found that rowing in sync on a rowing machine reduced rower's pain tolerance, allowing for increased athletic performance (Cohen, Ejsmond-Frey, Knight, & Dunbar, 2010). It is believed that synchrony creates a heightened endorphin surge that may explain the sense of euphoria people experience when performing embodied activities in sync, such as dancing, music-making, and marching. We believe that intertwined systems' abilities to sense user's rhythms and use their actuation components hold great potential for the facilitation of synchrony. With a cadence sensor mounted on the bikes, it seems feasible to imagine how an intertwined system is able to sense any rhythm and help riders achieve synchrony, so not only supporting them to stay together, but also to synchronize their leg movements.

Interviews suggested that the alignment of the Arm-A-Dine's agency across the two participants was a great contributor to its success. As we had connected the robotic arm wirelessly to the camera attached to the other diner's vest, participants were able to play with the alignment of the machine's agency. Their "natural" facial expressions controlled the interactions initially, but then participants quickly learned that they could also make alternative, playfully exaggerated expressions to gain more control over who received the food from the arm. When partners realized this possibility for control, they tried to make the participant laugh, to "control" what the camera sensed (seeing a happy face). In these ways, the alignment of the machine's agency was physically distributed amongst the participants. We can imagine in a future version of this system that the two mobile phone cameras talk to one another to sense when both partners laugh at the same time, rewarding them with a special treat.

The "EduExo" is not connected to other exoskeletons, however, we can easily envision a wireless augmentation that allows the exoskeleton to talk to other exoskeletons. As we recommend distributing alignment, we would suggest aligning the machines' agencies with one another in the first instance, so that, for example, two laborers could work in sync when trying to lift a heavy object together. Hopefully, this would help reduce misalignment issues that can often occur when trying to lift heavy objects together, such as when one person lifts up too fast, putting more burden on the other person.

10 LIMITATIONS AND FUTURE WORK

Our insights are primarily informed by prior work and our craft knowledge acquired through our practice in our design research lab. Our framework's strength arises from a practice-based orientation in a design tradition that is tightly linked to technology implementation (Mueller et al., 2022). This grounding enables us to develop insights that are readily applicable to design practitioners. However, this approach has inherent drawbacks, as previously pointed out (Höök & Löwgren, 2012). These include the prospect that our work might need to be altered in order to be generalized to new technology. Furthermore, we acknowledge that our framework is only validated through our own applied work and our team's reflections. Further work is needed to evaluate the framework. For example, design competitions could be conducted, in which one group is equipped with the framework, another group is not, and the two groups' results are compared. We could also evaluate how many designers have used the framework (and how) after it has been published, as done in prior work (Velt, Benford, & Reeves, 2017).

We acknowledge that we have only begun to fully understand the role of the human body in our intertwined experiences. In particular, we acknowledge that some of our four quadrant names could also be used to describe experiences around less embodied systems. For example, we can easily envision interactive virtual agents that can be described as influencer or butler. Microsoft's infamous "Clippy" could be regarded as such a butler. This may be due to the uniqueness of these experiences, as the vocabulary needed to capture and describe such experiences has not been necessitated until now. Having said that, we do believe that the names "adversary" and "angel" are more specific to embodied experiences. We did consider more specific names, such as "ghost that guides your bodily movements", however, found these too long.

We also acknowledge that we have yet to fully explore how software advances such as artificial intelligence can support intertwined experiences. In our systems, we have drawn on prior data to make inferences about possible future states. For example, in Ari, the eBike, we used our past location and speed data to make inferences about where the rider will be located at future points in time. In the future, we can envision an enhanced software component that uses larger data sets not only from our own work with our own bike, but also data from all previous rides, and possibly even data from other riders. This would not only allow for more accurate engine support, but also improve safety by using awareness of other eBikes nearby to avoid congestion on narrow bike paths.

In Arm-A-Dine, machine learning enabled the camera-based emotion detection that informed the robotic arm movements. More training data sets could result not only in better detection rates, but also inform more smooth arm movements that could, complemented with additional sensors, result in movements of the robotic arm that would be more aligned with the movements of the user, such as torso movements. Taken together, these experiences suggest that with software advances such as artificial intelligence and other enabling techniques higher levels of intertwindness could be achieved, as it allows to predict future action more accurately.

Of course, sharing agency with a computational machine does not only have benefits. In particular, as we are concerned with the role of agency in the resulting user experience, we point out that sharing agency can often mean that the user experiences a loss of agency that can affect how they regard any autonomy of the computational machine and maybe even their own. For this, we point to prior work that highlighted that designers should "adopt a critical understanding of human and non-human agency, given the potential benefits and threats that intelligent agents engender given their increasing autonomy, especially in relation to the ways in which agents are able to influence us in everyday life." (Rozendaal, Boon, & Kaptelinin, 2019). In particular, prior work that examined interactive systems that can act autonomously has found that the ability to "anticipat[e] and control[e] the situation" in which the user find themselves allow to better address problems that call for behavioral changes such as in the areas of sustainability and health (Ghajargar & Wiberg, 2018). However, ill-intentioned state, industrial or special interest group actors could use the same techniques to act against the interest of the user. We therefore point to the need for future work to investigate how technological advances that lead to more autonomy in systems affect our notion of agency and how we can guide designers in utilizing it in ethical and responsible ways.

Furthermore, we acknowledge that we have yet to consider supplementary ways to support the four user experience quadrants, such as through employing additional systems that complement our intertwined devices. For example, we can envision an intertwined system that aims to support users in a behavior-change activity, such as with the aim to increase physical activity during the day. The system would "nudge" the user to be more physically active by suggesting "more" movement whenever it senses initial movement. Such a system could be complemented by a smart tangible object in the person's vicinity that provides information about past movements to encourage reflection on what has worked previously.

Prior work around the design of reflection-supporting systems (Ghajargar, Wiberg, & Stolterman, 2018; Hallnäs & Redström, 2001; Jung, 2020) could be useful here to complement our knowledge.

We also acknowledge that, at this stage, our framework is limited to a specific group of users. Future work can consider additional groups. These groups could include people with physical impairments, whether permanent or temporary, like the injured. More precisely, we believe our work might be useful for injury rehabilitation efforts, for supporting growing bodies such as children's, and possibly for helping the elderly to cope with their reduced bodily capabilities. Future work could shed light on whether our hopes in this regard are justified.

Another limitation of our work is that we have not yet considered the long-term use of intertwined systems. With extended use, there exists the prospect for many of the unique interactions that these systems afford to transition from the conscious to the subconscious (Danry et al., 2022). Not only can such transitions habituate the use of the system, they can also change the user's brain via brain plasticity. We point to artist Neil Harbisson who has a condition that prevents him from seeing colors and has worn an implanted camera to allow him to "hear" colors through bone conduction. After having used the system for several years, scans of Harbisson's brain suggest that he has been starting to "see" colors rather than transform any sound information into color representations, implied by "significant changes in functional neural patterns, structural connectivity and cortical topography" (Alfaro, Bernabeu, Agulló, Parra, & Fernández, 2015). We, therefore, believe that future work should investigate long-term effects in order to understand the potential these systems have to change our bodies and hence who we are, as has been suggested previously (Clark, 2001; Mueller & Young, 2017, 2018).

We also highlight that our notion of both intertwined human-computer integration specifically, but also integration in a broader sense, speak to prior work that has previously stressed ethical implications which arise in instances where the human body and the computational machine are brought closer together. For example, Grosz pointed out that although we have come away from a traditional cartesian dualism of mind-body separation, we still have a long way to go to fully understand people's bodies and in particular their differences and how to engage with them academically, meaning that there is also still a long way to go when it comes to fully understand how to design technology for such bodies (Grosz, 2020). Furthermore, we also note that prior work proposed that how we treat human bodies has a close connection with how we treat nonhuman natural environments (Warren, 1997), meaning that our work could also be speaking to the design of intertwined relationships with nature, however, we leave this for future work.

We also acknowledge that we have taken a rather positive view of the future of intertwined systems. We are aware that matters of agency over users' bodies can result in negative consequences. Therefore, we urge future work to carefully interrogate matters of agency. Methods for approaching such interrogations already exist, for example, see dark patterns (Greenberg, Boring, Vermeulen, & Dostal, 2014); we believe that these could be readily applied to our work. Furthermore, our work on intertwined human-computer integration revealed potential benefits, but also challenges that emerge through the adoption of the approach. We point to prior HCI work that proposed to go "beyond" (Hollan & Stornetta, 1992) particular research visions and instead aim for alternative approaches. Similarly, we point out that an "intertwined" approach is but one of many potential paths to reach human-computer integration and encourage future work to explore what lies beyond or in parallel.

11 CONCLUSION

This article was written in response to the trend of integrating the computational machine and the user's body, underpinned and driven by technical advances that allow sensing and actuating of the human body in ways that enable the user and the computational machine to share agency. This trend can enable novel and intriguing bodily experiences, relevant already today in "everyday" application domains such as mobility as in our eBike case study but also for developments around cyborg futures that envision more advanced prosthesis and discuss the possibilities of interactive implants etc. (Mueller, Kari, et al., 2020), in which users find it difficult to separate their individual contributions and those of the machine. However, as prior work points out, the appropriate design of these systems has been insufficiently explored.

Our research offers a stepping stone toward an understanding of how to design intertwined systems. We argue that in order to contribute to design knowledge in this area, it is beneficial to first understand the associated user experiences. To facilitate this understanding, we have reported on our experiences of designing such systems and the associated user studies. Based on this work, we have articulated a framework incorporating the interaction of two key dimensions of intertwined systems: awareness and alignment of the machine's agency. This framework has allowed us to articulate a design space and a set of design strategies to assist designers in making informed decisions when designing future systems. We believe that these contributions can help exploit the unique opportunities that exist when the human body and the computational machine intertwine.

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