Integrated Exertion – Understanding the Design of Human–Computer Integration in an Exertion Context

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Human-computer interaction (HCI) is increasingly interested in supporting exertion experiences so more people can benefit from physical activity. So far, most systems have focused on sensing and presenting information to the user via screens to support the exertion experience. Interestingly, emerging technology can also act on the exerting user's body based on sensed information, granting researchers the potential to develop technology that not only "presents" but also "acts" on information throughout an integrated exertion experience. As a result, design opportunities surrounding computing machinery as contextually aware exertion partners are now available. However, there are currently no frameworks to guide the design of human-computer integration in an exertion context. To contribute to closing this gap, we designed three eBike systems to investigate different forms of integration with the exerting user and we studied the resulting user experiences. Based on the results of these three case studies, we present the first framework, including associated design tactics, to offer guidance on how to design human-computer integration in an exertion context.

CCS CONCEPTS •Human-centered computing~Human computer interaction (HCI)~Interaction paradigms~Collaborative interaction

Additional Keywords and Phrases: Human-computer integration, whole-body interaction, exertion, bike, cycling.

1 INTRODUCTION

Human-computer interaction (HCI) is increasingly interested in supporting exertion experiences so more people can benefit from physical activity [3,52,61,64,66,97]. From whole-body movement gestured based interfaces that invite learning about and performing physical activity [56,92], to wearables that can measure and quantify human performance [23,44], virtual and mixed reality sporting competitions [59,100], to emerging systems in contact with the human body that can sense, interpret data and perform an actuation in the context of the experience to partner with the user [5,79,90]. In this paper, we argue that the emerging trend of contextually aware exertion systems as supporting partners can result in novel exertion experiences where the user's abilities could be extended to go further, faster and in a safer way. However, when the system performs an actuation while in contact with the user's body, this can result in

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control negotiation moments of varying degrees - leading to an emerging design space that offers promising opportunities and challenges to further exertion supporting systems and benefit more people.

We consider exploring exertion experiences, where the user invests physical effort [60], from human-computer integration, where the system can sense, interpret and act on the experience [38], as a helpful perspective to examine the emerging trend of contextually aware exertion systems supporting partners - an intersection we call 'integrated exertion' where the user invests physical effort and the system can extend the user's abilities by performing contextually aware actuations that also result in control negotiation moments that must be considered when designing for integrated exertion experiences.

Since there are many exertion experiences where we could study integrated exertion, we decided to use electric bikes (eBikes) to narrow our scope because eBikes can be modified with sensors, actuators and programmed to sense, interpret and perform an actuation to assist the user while investing physical effort. Also, eBikes are used globally and are growing in popularity [32,47,81], providing an opportunity to benefit a large number of users.

We present three qualitative explorations on integrated exertion: first, an eBike that senses the rider's leaning forward posture to embrace speed and simultaneously increases engine support to afford the rider a super-power experience. Second, an eBike that senses traffic light data and the rider's speed to increase engine support when the rider needs to go faster to cross the next traffic light on green. And third, an eBike that senses the rider's peripheral awareness directly from their neural activity to provide engine support when the rider is safely and openly engaged with the environment. These case studies investigate different forms of extending the user's abilities using various data, sensors and actuators, resulting in varying degrees of control negotiation moments and eliciting different user experiences.

The learnings from designing, building and studying these case studies guided us to conceptualise the first "integrated exertion framework" that distinguishes two dimensions: the first dimension is "the type of support offered", and it spans *extending the user's abilities* and *challenging the user's abilities.* The framework's second dimension is "the degree of user-system control negotiation", and it spans *low control negotiation* to *high control negotiation.* Finally, we identify the experience quadrants that arise when we map these two dimensions against each other to present integrated exertion systems as *partners, assistants, detractors,* and *thrillers*—resulting in twelve integrated exertion sub-experiences with design tactics for the design of future integrated exertion systems.

Our contribution to HCI is around "control", where the human body is tightly coupled with an actuation enabled system. Here, we reflect on opportunities, challenges, and ethical considerations when integrated exertion technologies create "control" negotiation moments and how we might consider these moments and their evolving nature as a design opportunity to balance with the design intent of the systems we build. We believe this work is of utmost importance today, as technologies continue to come in closer proximity to our bodies to support exertion experiences with the capacity to sense, interpret and act on the experience. Failing to design this experience with thoughtful consideration could create unfair, limited, and exclusive situations. As such, our work presents the integrated exertion framework to outline possible optimistic and potential malicious integrated exertion user experiences that we, as technology designers and visionaries, can work towards to support healthy engagement with technology.

2 RELATED WORK

To develop our integrated exertion framework, we have drawn from related work on exertion, bodily integration, integration and HCI works on cycling. Lastly, we present the research gap and articulate how we aim to close this gap by answering our research question.

2.1 Exertion in HCI

In this section we describe how the integration thinking on supporting exertion experiences is evolving by discussing various bodily integration applications. We then explain how HCI has specifically supported cycling experiences, and lastly, we present the research gap our work contributes to.

The first paradigm supported exerting users by allowing them to track their athletic performance through a generic interface, commonly a keyboard, enabling to enter their exercise achievements, such as the number of push-ups they had completed. The second paradigm replaced the keyboard with movement sensing. For example, interactive mats could sense the user jumping [20,110]. The third paradigm allows experiencing the exerting body as play through integrating the digital with the human body [40,62,67,77]. We are inspired by this prior work and believe that integrating the digital with the human body can also be beneficial for us as we know from previous research that exerting users can feel integrated with their sports equipment, such as riders with their bikes [93]. However, our knowledge about how to design such integrated experiences is still underdeveloped [9,25,29,62,66], hence our work is still needed to further the design of integrated exertion systems.

In particular, we note that technical advances allow integration systems to not only sense, but also actuate the human body, for example through motors that move the user. As such, we are interested in the design of systems that can both sense and actuate the user, allowing for unique and novel integration systems, for example [55,79]. However, despite a proliferation of integration systems, there is still not much theoretical knowledge about the associated user experiences, which hinders our understanding of how to design such systems. Prior work around bodily integration provided some of this understanding, which we discuss next

2.2 Bodily Integration

We also learned from prior work around bodily integration; by bodily integration we mean a fusion between the human body and the computational machine as people can experience with bikes [93]. In our quest to understand the design of integration for exertion experiences, we were guided by prior work that appears to have identified three different types of bodily integration: non-acting bodily integration, enacting bodily integration, and stimulating bodily integration. We now discuss what we have learned from each.

2.2.1 Non-acting bodily integration

We learned that where humans interact with objects that are in contact with their body, such as a tennis racket or a bike, the brain can temporarily integrate these objects *into* the image of the body [11,17]. Our mental construct of the body, or body schema, arises from visual, tactile and proprioceptive information to compose an awareness of our body including limbs in space, and interestingly, this can be extended to include objects that have a systematic relationship with the body [16]. These inclusions into our body schema are often temporary and situational. For example, if the rider stops cycling and steps off the bike, the bike is no longer part of the body schema, and the rider does not experience a sense of loss of ownership over the bike as if it was a part of their body [31]. This insight taught us that systems when in contact with the human body while being used can result in bodily integration experiences, supporting the exertion activity. We made use of this in our work on eBikes, allowing the rider to integrate the eBike into their body schema while cycling. However, this knowledge about bodily integration is derived from traditional, non-interactive systems such as bikes, hence does not (yet) make use of the opportunities interactive systems offer to bodily integration. We now turn to related interaction design work on systems for bodily integration and discuss what we have learned from them.

2.2.2 Enacting bodily integration

Enacting systems can act on data to support the user experience. For example, the integration system's software uses algorithms to interpret sensed data about the user or context during the experience [37]. The interpretation of the data leads to the system performing an actuation to its system, for example, actuating the electric engine of an eBike to go faster to support the user in the activity context. The actuation can happen without the user needing to command the system to perform it as the system can act on the experience. As a result, HCI researchers and sports enthusiasts have begun exploring enacting systems to support the exertion experience. For example, De La Iglesia et al. [30] created a cycling system that senses the route's slopes to increase pedalling difficulty as a way to challenge the rider to improve their physical fitness. Another example is the work by Sweeney et al. [96]. The authors' eBike senses pollution levels on the road ahead so that the eBike increases engine support as a way to reduce the rider's effort and hence breathing rate, and thereby helping them avoid breathing in too much polluted air. We were also inspired by the "Heart rate eBike" [57] that regulates its engine support in response to the sensed heart rate of the rider; providing greater support when the user's heart rate is too high. Similarly, the "e-Sweat Bike Assist" system [72] senses physiological signals (a sweat threshold) and increases engine support to prevent the rider from perspiring too much.

We learned from these prior works that bodily integration systems can act on data to support the exertion experience. We also learned from these systems that the data to support integration systems can come from the environment, such as air pollution data, and the exerting body, such as sweat data. We used this knowledge and explored traffic light data coming from the environment in case study 2 and neural activity data coming from the exerting body in case study 3. However, the associated articles mentioned above focused primarily on technical implementation details and hence offer only limited guidance on how to conceptualize and design for the user experience; hence our investigation is still needed.

2.2.3 Stimulating bodily integration

Stimulating bodily integration systems stimulate the human body by using, for example, electrical muscle stimulation (EMS), transcranial stimulation or galvanic vestibular stimulation. However, they differ from enacting bodily integration systems because they do not actuate things like the eBike's engine or the exoskeleton's arm; instead, they actuate parts of the human body to facilitate a human-machine integration [36,89,111]. For example, in the game Balance Ninja [24,25,40] galvanic vestibular stimulation alters the player's sense of balance via an electrical current triggered by the player's opponent to create an engaging experience. In "PossessedHand" [98], EMS guides hand movement to support learning how to play a musical instrument. In Affordance++ [55], EMS actuates the user's arm muscles to cause an interaction with an object to emerge, such as shaking a spray can before spraying. Finally, in FootStriker [105], EMS stimulates a runner's calf muscles to control the foot angle before landing and improve running technique.

From these works, we learned about the diverse forms of data that can be used with an integration system and the many forms in which the system can act on data to support the user experience. In our three case studies, we do not stimulate parts of the human body but focus on enacting bodily integration using movement, traffic lights, and neural activity data to actuate the eBike's engine and explore the resulting integrated exertion experiences.

2.3 Human Augmentation

Our work also responds to research into human augmentation [1,9,45,82,104]. Human augmentation focuses on enhancing a user's sensory perception, cognition and actions. These enhancements are often achieved via technology that can be invasive or non-invasive in relation to the user's body. One example of a non-invasive human augmentation that enhances sensory perception are thermal imaging glasses that allow users to see heat [86]. The issuing of reminders, triggered by a user’s location, by time and by other events, extend the user's cognitive ability to remember tasks in the future. Action can be augmented in a variety of ways. While telesurgery [87,106] allows a surgeon to conduct a procedure some distance away by mapping their fine motor movements to a robot, exoskeletons can amplify a worker's strength [4].

Examples of invasive human augmentations include implants. For example, artist Neil Harbisson has an implant that is connected to a camera that transforms light frequencies into musical notes, allowing him to experience otherwise imperceptible colours as sound [1]. In the medical domain, brain implants have been used in the bionic eye [78] to stimulate neurons that can restore a sense of vision to the user.

Invasive and non-invasive technologies can augment user's sensory perception, cognition and actions [82,86]. These examples above cover a wide range of applications and provide a contrast to enacting bodily integration systems, as augmentation systems partly live in the 'interaction' paradigm, that is, requiring a form of user input to generate an output. For example, considering when to use the exoskeleton's strength, setting configurations of reminders to locations, and choosing what part of a landscape to scan to receive a musical note. On the other hand, enacting bodily integration systems can act on data without the user's input. This contrast raises questions about how we should design integration experiences, especially in an exertion context that often is time-critical due to the user exerting. Throughout our three case studies, we explore this question to provide an initial set of design guidelines presented alongside the framework.

2.4 Bikes and HCI

As we used eBikes as our research vehicle to investigate the design of bodily integration in an exertion context, we also learned from prior HCI works on bikes.

eBikes (electric bikes) are gaining global popularity most likely because eBikes provide electrical assistance that helps riders go further and faster [39,80] and they support environmentally conscious choices.

Prior HCI work on cycling mostly focused on traditional (non-electric) bikes. Rowland et al. [85] explored the design of mobile phone–based app experiences for cyclists using GPS. The authors concluded that bike “design has to respect the distinctive nature of cycling and needs to carefully interweave moments of interaction with it”. From this work, we have learned that interactive technology can support the cycling experience but needs to be carefully designed to limit interruptions to the user at when it performs an actuation. We tried to consider this in our eBike designs. Bolton et al. [21] developed an immersive exertion game that combined virtual reality with an exercise bike. From this we learned that interactive technology could support the “joy” of cycling, and we considered this in our designs when we aimed to support also experiential aspects of cycling. We also learned from prior work around the use of stationary exercise bikes to support exertion-based learning activities in the classroom by using the bike as an input controller [2]. We learned from this prior work that augmenting a bike can result in many opportunities and that cycling can be much more than a mode of transport from point A to B, and we have hence tried to embrace the experiential aspects of cycling in our design process.

Taken together, we learned from these diverse prior works that interactive technology can support a more engaging cycling experience and that there are not only instrumental aspects, such as getting from point A to point B in the fastest way. Consequently, we explored how integration can support the cycling experience holistically, both considering experiential aspects and instrumental aspects.

2.5 Gap and Research Question

Prior work highlights that the design of integrated exertion experiences lacks guidance for designers who aim to create such systems. Bikes appear to be helpful research vehicles to investigate this, as a) they have been explored in HCI before, b) are known to integrate with the human body from traditional cycling, and c) are used worldwide, and improvements can benefit a large number of people. However, what is still lacking in understanding the user experiences that integrated exertion systems could facilitate is developing the associated design knowledge to support the design of integrated exertion systems. We point to this gap in knowledge and propose to begin filling it by exploring the design of three different eBike systems to inform an integrated exertion experience framework. As such, we are asking the research question: how do we design integrated exertion experiences?

3 METHODS

We now present the methods used to explore and inform the integrated exertion framework.

3.1 Gap and Research Question

Research through design (RtD) artefacts are designed as objects of enquiry into a probable future [42,108]. Importantly, in RtD, the research outcomes include design artefacts and the accompanying insights [42,51]. In our case these artifacts were eBikes that used different data types to facilitate different integration experiences and support our enquiries into a possible integration future. With respect to insights, we carried what we learned from our work with each prototype over to our work with the next prototype. Our approach, like the approach of prior work, used RtD to generate theoretical frameworks [25,25,50,65,99] including design strategies [8,67,101].

3.2 Semi-structured Interviews (*used in all case studies)*

We used semi-structured interviews for all case studies as it allows us to select questions that support the flow of the conversation and can lead to nuanced insights [18]. We utilised as a part of the interview process prompts to elicit conversation from participants, for example, in case study 2, a data visualisation showing when the system increased engine support was shown to participants to encourage them to tell, from their own perspective, what had occurred during those moments. In case study 3, we recorded the EEG data from participants interacting with the system and offered this as a visualisation during the interviews to invite further comments and reflection.

3.3 Explicitation Approach (*used in case study 2 and 3)*

The explicitation approach [102] is a retrospective interview technique that seeks first-person accounts of an experience immediately after it has occurred. The researcher asks the participant questions about specific moments of the experience chronologically to understand the participant's perspective on how things unfolded and capture rich tactile details [41,76]. To utilise this approach and capture user experience details, we designed the cycling course in case study 2 (1.2 kilometres) and case study 3 (1.5 kilometres) so that participants could cycle the course once or twice and come back to the starting point for a short "explicitation approach interview" before heading out to complete more laps. This protocol allowed us to capture the experience "as it happened" between laps, and it encouraged participants to reflect on fine experience details to articulate differences in relation to the different data types and the resulting user experiences reported in the framework.

3.4 Field Deployment (*used in case study 1)*

Field deployments have been used by researchers who wish to focus on the user's understanding and usage of a novel technology system rather than its technical feasibility [19,43,48]. In case study 1, we experimented with this approach by deploying the prototype to participants' homes for two weeks. This approach invited participants to self-document their observations in a diary based on how they used the system in their cycling context.

3.5 Thematic Analysis *(used in all case studies)*

Qualitative analysis focuses on deriving meaning from data, often in the form of themes [26]. A theme is a collection of labels, with each label describing something important about the data, the collection of labels then leads to a theme in the data. Thematic analysis offers a process to derive labels leading to themes grounded in the data [26]. Our thematic analysis began by familiarising ourselves with the data from each of the case studies through transcribing the audio recordings and importing them into Nvivo [34]. We also included photographs with short descriptions of the context in which they were taken and what they were showing. As a second step in the analysis process, two of the authors independently added labels to the data. Next, the two authors used a mind map to review and compare the labels for each case study and capture resulting themes and their relations. This process was followed by various meetings where we refined the themes in relation to the research question 'how do our eBike case studies help us inform a framework to better approach the design of human-computer integrated exertion experiences?'. We now introduce each of the case studies and how they help us inform the framework.

4 CASE STUDY 1: AVA THE EBIKE

"Ava, the eBike" [6] explored the design of an integrated system that acts on the user's movement data to support the exertion experience. Namely, Ava acts on the user's leaning forward body position to synchronously increase engine support. This response is achieved by reading gyroscope data off a smartphone attached around the rider's chest to wirelessly activate the eBike's engine support.

Figure 1. Ava senses the rider's leaning forward body position to activate the eBike's engine support.

Ava's design was inspired by how cyclists commonly lean forward when they invest physical effort to go faster, climb a hill, and ride down a hill [5]. We explored leaning forward as a form of bodily acceleration that activates the eBike's engine support while allowing the rider to focus on the road. We also designed a sound (which can be turned off) delivered through a handlebar-mounted speaker. This feature was inspired by the experience of wind becoming louder in the rider's ears as they accelerate or the sounds of motor vehicles accelerating such as cars and motorbikes. The goal was to amplify the sense of acceleration as the rider leans forward and the eBike accelerates.

4.1 Technical Implementation

"Ava" was built around an "Hybrid" eBike with 250W nominal power [112]. The rate of acceleration responds to the angle at which the rider leans forward. We designed the system to provide brief acceleration as the rider leans forward and extended acceleration if they remain leaning forward. For safety purposes, we mounted a linear Hall effect sensor to detect handlebar displacement so that if the rider is leaning forward and turning sharply, the engine support is disabled.

Figure 2. Ava the eBike.

4.2 Study of Ava

A study with 22 eBike riders was conducted to understand the user experience of cycling with Ava.

4.2.1 Participants

We recruited 22 participants (female=10, male=12, no non-binary), aged between 24 and 55 years old (M=36.4 and SD=9.4) from Melbourne, Australia. All participants had been eBike riders for between three months and three years (Table 1).

Table 1: Participants' eBike cycling experience.

Number of participants	eBike cycling experience
10	3–6 months
7	7–18 months
5	19–36 months

4.2.2 Data collection and analysis

Participants hosted Ava for two weeks at their home and could use it as many times as they wished. After the two weeks, we conducted semi-structured interviews with the riders about their experiences. We used the participants' diaries to prompt them to describe their experiences to us. We recorded, transcribed, and analyzed the semi-structured interviews. The research team independently coded the data. We then synthesized the coding into themes and developed design tactics over the course of five team meetings

4.3 Towards Creating the Integrated Exertion Framework

This case study revealed that using movement data to facilitate an integrated exertion experience is viable. As participants changed the angle of their body, the system enabled a kinetic feedback loop where participants experienced the sensation of going faster through their body, allowing the participants to experience a sense of "superpower" to go faster resulting from leaning forward. For example, one participant stated: *"It is like the power comes from my body when I lean, and not from the engine, it makes me feel stronger." Another participant commented: "I like that the power is always there for you, I liked to use the body acceleration and take the curves exaggeratedly as if I was motorbike racing".*

Interestingly, moments of user-system control negotiations were only accidental as the user forgot to calibrate the gyroscope. This serendipitous event, led us to consider that further experimentation was needed to explore integration exertion, especially using other data types not controlled by the user, as is the case with leaning forward, to inform when and how much the system actuates

5 CASE STUDY 2: ARI THE EBIKE

"Ari, the eBike" explored designing an integrated system that acts on contextual data to support the exertion experience [7]. We had the idea that Ari could work with the rider to regulate their speed so that they can catch traffic lights on green. Ari combines traffic light pattern data sourced from traffic authorities and user speed data (via the eBike's speedometer and a global positioning system (GPS)) to either increase engine support or tell the rider to slow down via bone-conducting headphones. The study of Ari helped us understand how users negotiate control within an integrated experience via adjusting their exertion to regulate the speed and catch traffic lights on green.

5.1 Towards Creating the Integrated Exertion Framework

To better understand how riders would negotiate control in an integrated exertion experience, we began by conducting design workshops with the cycling community around our research lab, which includes riders from varied academic backgrounds such as industrial design, computer science, sustainable transport and HCI. We drew from their expertise to discuss, sketch and derive ideas to design the system. We identified the following safety features.

1. Feedback occurs regularly among partners when co-operating; however, when systems do not provide regular feedback to users, this can create friction [75]. This insight prompted us to consider how the system could communicate with the rider, especially as the rider needs to be aware of other riders and vehicles around them. In response, we used bone-conducting headphones, because they do not cover the user's ears and restrict their awareness of the surrounding environment. We limited the use of sound to two instances: first, a sound described as a "powerboost" is played when crossing a traffic light on green to reassure the rider that the system is working as expected; and, second, a "slow down a little" sound tells the user when to slow down to reach a speed that will get to the next lights on green.
2. For safety purposes, we designed the bike to cut off engine support when the brakes were engaged. We determined our reference speed through our local traffic authority's intelligent transport system where traffic lights are computationally programmed to change consecutively so bike riders during peak time can aim to travel at 22km/h to catch traffic lights on green as part of a "green wave". We built an iOS app to send the speed of the rider via Bluetooth to an Arduino to orchestrate one of three responses: first, if the rider's speed was below the reference speed, the engine would accelerate to assist the rider to meet the reference speed; second, if the speed of the rider was greater than the

reference speed, the slow-down message was played to let the rider know to slow down; and third, if the rider's speed was within +/−0.5km/h of the reference speed, nothing happened.

5.2 Study of Ari

Ari was studied with 20 experienced bike riders (female=6 and male=14, no non-binary), aged between 23 and 48 years (M=36 and SD=7.7). Our inclusion criteria were: first, participants had to know how to cycle so that cycling risks could be minimised; and second, that participants cycled at least once a week, so they could compare their recent cycling experiences with Ari. Ten of the participants had previous experience with eBikes, ranging from two weeks to four years of use.

5.2.1 *Setting*

The study lasted two months and it took place in mild weather, without rain, during weekday peak times between 4:00pm and 6:00pm to ensure the predictability of the traffic lights. The road used for the study was straight, offered bike lanes, had four traffic lights and was 1.2km long with a 24m incline. On average, participants took about seven minutes to cycle from start to end.

5.2.2 *Procedure*

We used two eBikes: Ari and a regular pedal-assist eBike. The pedal-assist eBike, or Pedelec, is the "default" eBike available in shops. Pedelec users access the engine's assistance by pedalling. We hoped that riders would be able to better compare Ari's approach in the interviews having used these two different bikes. We asked two randomly assigned volunteers to arrive at the same time so they would start cycling at the same time, simulating an urban cycling scenario where cyclists often share the bike path. The two participants, who did not know each other and were not instructed to cycle together, started cycling at the same time, one using Ari and the other the pedal-assist eBike. Participants started from the low-incline point and cycled to the end (through all four traffic lights). Once participants arrived at the end, they cycled back to the starting point. This step was not part of the study and Ari was not programmed to respond. Upon returning to the starting point, participants were interviewed before we asked them to switch bikes and cycle again. In summary, each participant had a cycling experience lasting approximately 45-minutes during which they cycled the selected road six times, and used each eBike three times.

5.2.3 *Data collection*

Each pair of participants was interviewed for approximately 50 minutes. We interviewed each pair of participants together after they completed one return leg of the course and before they switched eBikes to commence the next leg. This approach appeared to encourage the participants to be more observant when they retried Ari based on points raised during their interviews. Their further observations were then reported before the next switch of eBikes.

5.3 Towards Creating the Integrated Exertion Framework

This case study showed that it is possible to use contextual data (speed of the rider, their location in relation to the next traffic light and the lights' changing patterns) to facilitate an integrated exertion experience. When the system acted on the contextual data, the user experienced the increased engine support, resulting in a moment of user-system control negotiation where the user needed to apply their sensing abilities to scan the environment to determine if proceeding with the acceleration was safe. For example, one participant said: *"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.'"*

Taken together, the results from this study helped us to further understand user-system control negotiation moments in an integrated exertion experience. This has extended our knowledge about integration experiences where data was user controlled, as was the case with movement data from the first case study, in relation to how the user experience differs when the data is externally controlled, as is the case with contextual data. However, we acknowledge that a third state where data is semi-controlled by the user might be possible. To explore this, the next case study investigated semi-controlled data via the use of physiological data as part of an integrated exertion experience.

6 CASE STUDY 3: ENA THE EBIKE

"Ena, the eBike" explored the design of an integrated system that acts on the user's physiological data to support the exertion experience [10]. Ena uses an electroencephalogram (EEG) cap to monitor neurological activity in relation to the user's field of view. This data can be used to indicate when the rider has reached a state of peripheral awareness, or in other words, when the rider's field of view is wide rather than narrowly focused on a potential dangerous situation, like a veering car. Peripheral awareness is known to facilitate better athletic performance, coordination and awareness of the environment [53,73,74]. While in this state, the system offers engine support to assist the rider, and when rider exits the peripheral awareness state the eBike stops the extra engine support, slowing down the eBike and allowing more time for the rider to respond (such as breaking) to dangerous situations on the road.

6.1 Technical Implementation

We used an OpenBCI Cyton [95] and an Ag/AgCl coated electrode cap (BCI, 2019b), using the 10/20 electrode placement. Electrodes O1 and O2, with AFz as ground and CPz as reference stream data, and electroconductive paste was used to improve contact between the participant's scalp and the electrodes. This electrode montage was validated by previous studies assessing peripheral awareness (Figure 3) via EEG [53,73,74].

When the physiological data is between 0.76μV–1.19μV within the high alpha range of 10–12Hz, it corresponds to the rider being in a state of peripheral awareness. A connected Arduino uno signals to the eBike's engine controller when to activate or stop engine support. Continuous physical support is offered to the rider by the eBike's electrical engine when the EEG signals correspond to the rider being in a state of peripheral awareness, which is known to facilitate better athletic performance, coordination and awareness of the environment [53,73,74].

Figure 3. Ena in action (left). Data is streamed via electrodes O1 and O2 (top), with AFz as ground and CPz as reference (bottom).

6.1.1 Deriving a peripherally aware state from EEG data

We used previous study data [73,74] to set the peripheral awareness target values for our study. We took the mean voltage values exhibited by individuals in a state of peripheral awareness and created a range of two standard deviations from the mean. The EEG raw data was collected at 250Hz and streamed via Bluetooth to a laptop placed in the eBike's pannier for signal processing using OpenBCI [95]. Fast Fourier transforms (FFT) at a rate of 1024/s were applied to the raw EEG data. Furthermore, a bandpass filter of 7–13Hz was applied to single out frequencies which have been demonstrated to be associated with peripheral awareness in the context of the electrode montage we have adopted [73,74]. To assess the rider's engagement in peripheral awareness, the calculations were performed in real time while riding Ena. When a rider's values fell between 0.76μV–1.19μV within the high alpha range of 10–12Hz and 0μV–0.7μV within the beta range of 12–13Hz, the software inferred that the participant was in a peripherally aware state. Values falling outside these parameters indicated that the participant was not peripherally aware (Figure 4). The addition of beta was used in reference to alpha to ensure signals that reached the desired alpha pattern were not a product of noise across all bandwidths. This was further complemented using a mean smoothing filter to mitigate movement artefacts [12]. Lastly, the values were used to calculate an output Boolean of "true" when participants were peripherally aware and "false" when participants were not.

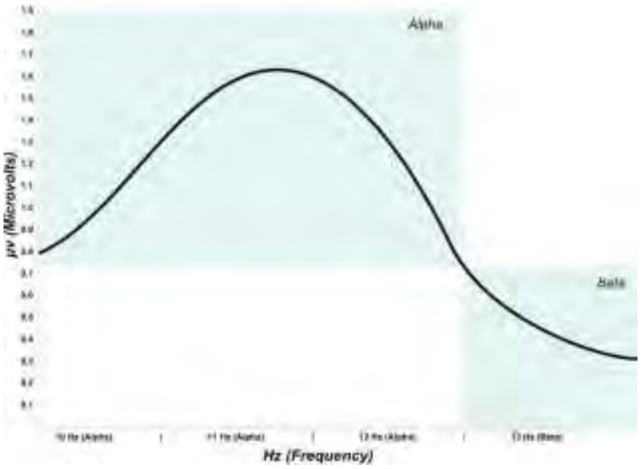

Figure 4. If the FFT above is in both the green zones, it suggests that the user is in a peripherally aware state.

The output Boolean was then sent to the Arduino board at a rate of 56,700 bits/s. The Arduino interfaced with the eBike's engine via a digital-to-analogue converter. Once the Arduino found the Boolean to be "true", it output a command to activate engine support; when the Boolean was "false", it output a command to terminate engine support.

In designing the system and study, we took three risk management measures. First, when the user engaged the brakes, the eBike's engine support was terminated regardless of EEG state. Second, Ena was designed to offer engine support gradually, because we found that an aggressive increase could be perceived by the rider as danger and lead them to narrow their field of view. Third, we only recruited experienced bike riders.

6.2 Study of Ena

Ena was studied with 20 bike riders (female=8 and male=12, no non-binary), aged between 24 and 58 years (M=39.8 and SD=10.5). Our inclusion criteria were: first, participants had to know how to cycle so that cycling risks could be minimised; and second, that participants cycled at least once a week, so they could compare their recent cycling experiences with Ena. Seven participants had previous experience cycling eBikes, ranging from two weeks to four years.

6.2.1 Setting

The study lasted three months and it took place in mild weather, without rain, in the afternoon on a suburban street. The road used was straight, flat, about 1.5 kilometres in length and it did not have traffic lights. We selected this road as riders could cycle continuously without stopping and it often had bikes, pedestrians and vehicles to offering a realistic setting. It took participants approximately seven minutes to cycle from the start to the end and return to the starting point.

6.2.2 Procedure

Before the study began, we ran a sports science video exercise that guided the participants to practise reaching peripheral awareness [107]. This was followed by the researchers placing the Ag/AgCl coated electrode cap on the participant and connecting the system. The participant then cycled the course twice while trying to access their peripheral awareness. Upon returning to the starting point, we asked participants if they had experienced the system increasing engine support and we also reviewed the collected EEG data to see if, and for how long, they had reached peripheral awareness. When a participant did not reach peripheral awareness, we invited them to watch the video again and practise cycling a few times. All the participants were able to reach peripheral awareness while cycling before proceeding with the study. Then, participants proceeded to cycle the course a minimum of six laps, as this would offer approximately 40 minutes of total cycling time. In between laps, we conducted five 10-minute interviews.

6.2.3 Data collection and analysis

We collected EEG data from all participants that showed when and for how long they had reached peripheral awareness. Participants were given access to this data during their interviews.

6.3 Towards creating the integrated exertion framework

This case study showed that facilitating an integrated exertion experience using physiological data was possible. Using physiological data resulted in moments of user-system control negotiation. For example, when a rider reached peripheral awareness, it was experienced as a feedback loop about their bodily state. However, when the system stopped providing engine support, participants experienced the system acting on the situation. The following quote explains this: “It was coming from my brain wave, but the system could slow down before I could act on to hit the brakes, it was uncanny but useful.” Taken together, this case study helped us extend our understanding of how semi-control over data affects user-system control negotiations, furthering our knowledge about how to design integrated exertion experiences. In the next section, we take this knowledge, gathered through the three case studies, to derive the first attempt at a framework for the design of integrated exertion experiences.

7 THE INTEGRATED EXERTION FRAMEWORK

We now present the integrated exertion framework. It is based on the knowledge we gained through the design, implementation, and study of the three case studies. We present a visualisation of the framework using a two-dimensional chart to show the design space that integrated exertion offers for HCI practitioners. This visualisation of a design space containing two dimensions was employed in previous HCI works around bodily experiences and hence we believe it is also appropriate here [25,63,67,83,84].

The framework’s first dimension is “the type of support offered” and it spans extending the user’s abilities and challenging the user’s abilities. The framework’s second dimension is “the degree of user-system control negotiation” and it spans low control negotiation to high control negotiation. We identify the experience quadrants that arise when we map these two dimensions against each other and conceptualise twelve integrated exertion experiences.

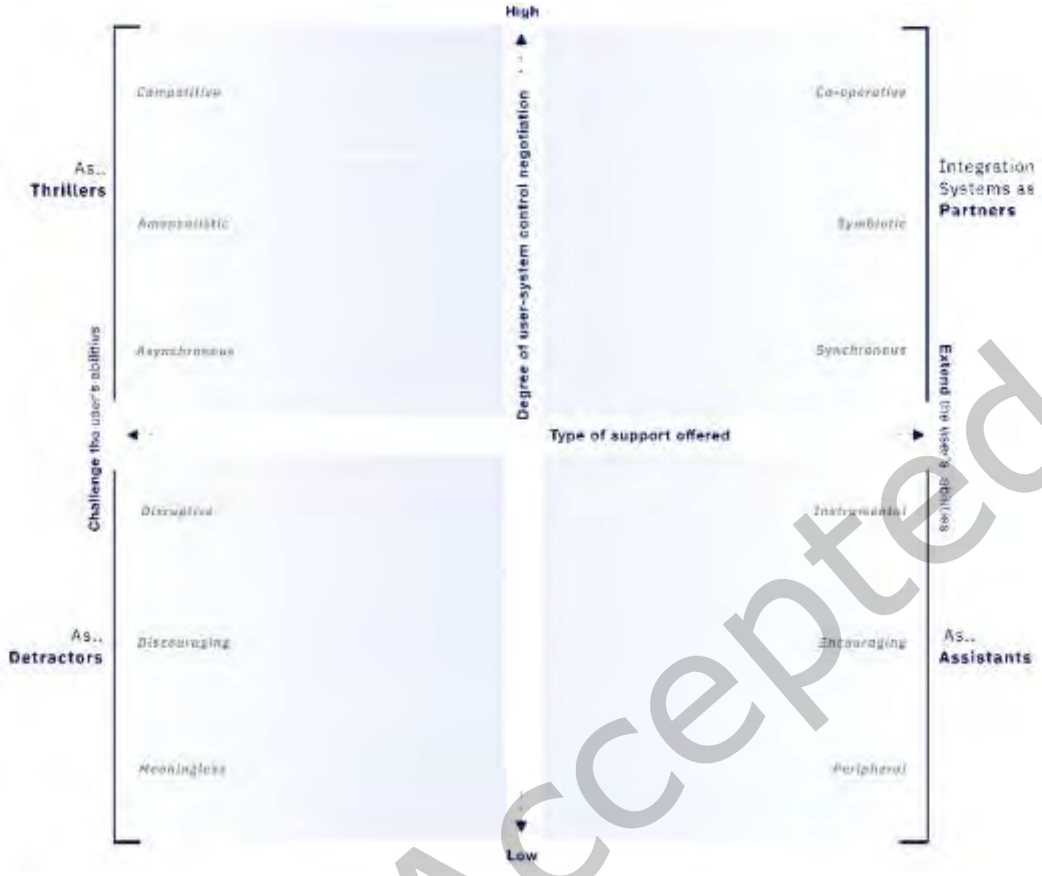

Figure 5. The integrated exertion framework.

7.1 The Framework's axes

The X-axis represents: "The type of support offered." At the far right of this axis, HCI practitioners can design a system to extend the user's abilities. For example, an eBike extends the user's ability to go faster. At the far left of this axis, HCI practitioners can design a system to challenge the user's abilities. For example, a gym spin bike can continuously become harder to pedal according to the user's cadence input, challenging the user's ability.

The Y-axis represents: "The degree of user-system control negotiation." At the upper end of this axis, HCI practitioners can design a system that can actuate without user command parts of the system. For example, Ari the eBike can actuate the engine to increase engine support upon sensing and interpreting data, resulting in a user-system situation where control is momentarily negotiated. At the lower end of this axis, HCI practitioners can design a system to support low user-system control negotiation. For example, when Ari the eBike whispers in the rider's ears to slow down, this form of system actuation to whisper based on the interpreted data does not require user-system control negotiation as it only provides instrumental information to the user in the context of the experience.

7.2 The framework's quadrants

The framework has four quadrants within which we can articulate user experiences. These are experiences of integrated exertion systems as partners, assistants, detractors, and thrillers.

7.2.1 *Integrated exertion systems as partners*

Integrated exertion experiences in this quadrant involve systems that dynamically actuate control over the system to enable momentary user-system control negotiations that benefit the user.

User experiences in this quadrant

We describe three different ways in which the systems in this quadrant can act as partners.

Co-operative: the system senses contextual data around the task at hand, and uses this data to act on the experience to extend the physical or cognitive abilities of the user to achieving the task. This system design results in a high user-system control negotiation situation, in which the user does not control the contextual data that the system senses, interprets and uses to act.

Exertion example: as the user cycles and invests physical effort, Ari eBike senses and interprets the traffic lights data, and the speed and current location of the rider in relation to the next traffic light. It then actuates the engine when the user needs to reach greater speeds to catch the next traffic light on green. As the user experiences the acceleration resulting from Ari actuating the engine, the user negotiates control momentarily with the system; quickly scanning the environment ahead and determining whether they should go ahead at a higher speed or use the brake to slow down, while knowing that this boost is needed to catch the next light on green.

Symbiotic: the system draws upon the user's physiological data to act on the experience and extend the physical or cognitive abilities of the user. This design results in a medium user-system control negotiation situation, in which the user has some control over the physiological data that the system senses, interprets and uses to act.

Exertion example: as the Ena user cycles, the system senses physiological data such as EEG and identifies data patterns that are indicative of a user in a state of peripheral awareness (the user's field of view indicates full engagement with their surroundings). When the user is deemed to be in this state, the system increases engine support. While the user can be trained to reach this state of peripheral awareness with less effort, the occurrence or perception of a threat, such as a car veering toward the user, can lead to the user instinctively narrowing their field of view to focus on that threat and determine their course of action. In this situation the system can instantly stop engine support to give the user extra time to interpret the situation and respond.

Synchronous: the system draws upon the user's movement data to act synchronously with the user to extend their physical or cognitive abilities. This design results in a low user-system control negotiation situation, as the user has control over the movement data that the system senses, interprets and uses to act.

Exertion example: as the Ava rider cycles, and leans forward to embrace speed, the system simultaneously increases engine support. The user uses their bodily movement as the system's actuation control. Compared to the previous two experiences, the user-system control negotiation is low as Ava's actuation is paired to the user's movement.

7.2.2 Integrated exertion systems as assistants

Integrated exertion experiences in this quadrant involve systems that can act on the experience as an assistant to support the user. These designs result in user-system control negotiation situations in which the system is subordinated to the user and provides instrumental information, provides encouraging information, or performs actuations that are peripheral to the user’s experience.

User experiences in this quadrant

Instrumental: the system draws upon contextual, physiological or movement data around the task at hand, and uses this data to act on the experience and extend the cognitive abilities of the user. These actions involve the system providing 'instrumental' information that the user can act on to achieve the task at hand. The associated user-system control negotiation situation results in a moment of contemplation as the user decides whether to act on the instrumental information or not.

Exertion example: Ari’s feature to whisper in the rider’s ear to slow down to regulate the speed and catch traffic lights on green is an example of instrumental information that the user can decide to act on or not.

Encouraging: the system draws upon contextual, physiological or movement data around the task at hand and acts on the experience to extend the cognitive abilities of the user. These actions involve the system offering 'encouraging' information to support the user to achieve the task at hand. The associated user-system control negotiation situation results in a moment of encouragement where the user decides to act on the information or not.

Exertion example: The Nike music heart rate [103] system provides the exertion user with cheers from friends, generating a moment of encouragement that the exertion user might act upon by investing greater exertion effort.

Peripheral: the system draws upon contextual, physiological or movement data around the task at hand, and acts on the experience to extend the physical and cognitive abilities of the user. The system actuates peripheral information from which the user can benefit. The associated user-system control negotiation is very low to non-existent because the user barely perceives that negotiation to be part of their exertion experience.

Exertion example: An alternative version of Ava the eBike [6] offered automatic hazard lights to support the user by raising the awareness of those around them when the user’s cycling becomes unstable, for example when they have stopped and are resuming their ride. Ava provides this peripheral information, but the user barely perceives it during exertion.

7.2.3 Integrated exertion systems as detractors

Integrated exertion experiences in this quadrant involve systems that act on the experience as a detractor, drawing the user away from the situation. These actions lead to user-system control negotiation situations in which the system is subordinated to the user and aims to be disruptive, discouraging and offer meaningless actuations during the user’s experience.

User experiences in this quadrant

Disruptive: the system draws upon contextual, physiological or movement data around the task at hand to act on the experience and challenge the physical and cognitive abilities of the user by interrupting and drawing their attention away from the task at hand. The associated user-system control negotiation situation results in a moment of disruption of the user's control over the experience that the user then acts on.

Exertion example: Systems that have been designed to distract the user from the experience are often associated with persuasive technology, which aims to challenge the user's attitudes and behaviours through interventions [58]. For example, the Pavlok electric shock system [113] is designed to challenge the user's cognitive and physical abilities by abruptly delivering an electric shock. The shock is triggered by the user configuring the system on certain tasks, like running too slowly based on a given speed and GPS tracking. The user is briefly distracted from the experience and then tries to regain control.

Discouraging: the system draws upon contextual, physiological or movement data around the task at hand, and acts on the experience to challenge the cognitive abilities of the user. These actions involve the system offering information to discourage the user from achieving the task hand. The associated user-system control negotiation situation results in a moment of discouragement, during which the user decides to act on the information. For example, the user might respond by investing less exertion effort.

Exertion example: The Upright Go [114] senses the user's back posture. If the user slouches for too long, the system delivers a haptic pattern that discourages the user from slouching. This approach to using discouraging actions to change an experience might be useful for exertion activities that require fine posture to execute specific movements, such as combat, swimming, and dance. The associated user-control negotiation is momentary and extends only until the user decides to correct their posture.

Meaningless: the system draws upon contextual, physiological or movement data around the task at hand, and acts on the experience to challenge the cognitive abilities of the user. These actions involve offering a distraction from the task at hand. The associated user-system control negotiation is very low to non-existent because the user barely perceives the negotiation to be part of their exertion experience.

Exertion example: Imagine an eBike that senses pedalling cadence and when a certain exertion threshold is reached, it sends the user a text message with the link to a speed data log. This notification would be meaningless to the user during the exertion experience.

7.2.4 Integrated exertion systems as thrillers

Integrated exertion experiences in this quadrant involve systems that act on the experience as an opponent to the user and fight with them for control of the system.

User experiences in this quadrant

Competitive: the system draws upon contextual data around the task at hand, and acts on the experience to challenge the physical or cognitive abilities of the user towards achieving that task. These actions result in a high user-system control negotiation situation, as the user does not control the contextual data that the system senses, interprets and uses to act.

Exertion example: The Inferno Exoskeleton [115] is an exoskeleton system that uses contextual data to force its wearer to dance. Another participant (not wearing the exoskeleton) manipulates the limbs of a physical doll (connected to the system) and these directions drive movements in the limbs of the exoskeleton that force the wearer to move. The Inferno Exoskeleton produces continuous user-system control negotiation over the user experience resulting in a thrilling experience, while challenging the user's physical and cognitive abilities to let go or regain control.

Amensalistic: Amensalism is a type of symbiotic relationship where one species (the system in this case) provides a means to deteriorate the survivorship or fitness of another species (the user) without impacting its own fitness [70].

The system draws upon the user's physiological data, and acts on the experience to challenge the user's physical or cognitive abilities. These actions result in a medium user-system control negotiation situation, as the user has some control over the physiological data that the system senses, interprets and uses to act.

Exertion example: The Bronco Matic [13] is a mechanical bull ride that has been modified to read the rider's breathing rate and use this data to inform how aggressively the bull turns and spins. The Bronco Matic challenges the physical abilities of the rider as they need to fight against the bull's attempts to topple them. The system also challenges the rider's cognitive abilities as they need to focus to control their breathing rate (they retain some control). This experience is what we call symbiotic-amensalistic, whereby the Bronco Matic draws from the user's physiological data and aims to diminish the user's survivorship of remaining on top the bul. The characteristics of the Bronco Matic produce continuous user-system control negotiation over a thrilling user experience.

Asynchronous: the system draws upon the user's movement data to act asynchronously with them to challenge their physical or cognitive abilities. These actions result in a low user-system control negotiation situation, as the user has control over the movement data that the system senses, interprets and uses to act.

Exertion example: The Balance Ninja [24,25] system uses galvanic vestibular stimulation (GVS) to afford the user the sensation of vertigo by delivering an electric frequency to the mastoid bone behind the ear. The system delivers the electrical current based on bodily movement data and affords the user a thrilling experience that challenges their physical ability to remain balanced and their cognitive ability to focus on balancing their body.

7.3 Design tactics for designing integrated exertion including examples for positive and malicious futures

Each case study investigated a different form of data type to integrate with the exerting body, resulting in different user experiences. This section presents the recurring design tactics mapped to user experiences reported in the integrated exertion design framework. To illustrate each tactic, we also offer examples of future integration systems that could make use of them.

Tactic one: Shared control between the user and the system using different data types

Fine-tune the degree of control the user has over the system by exploring different data that informs when the system acts in the experience. For example,

1. “movement data” affords the user a high degree of control over the system acting in the experience as the user controls their body movement and therefore the resulting movement data used by the system.
2. “physiological data” affords the user a medium degree of control over the system acting in the experience, because the user can practice and gain some - but never full control - over their physiological data.
3. “contextual data” affords the user a low degree of control over the system acting in the experience as the data is sensed from the environment and the user does not have control over this data. In some cases, the user cannot perceive it, such as sensing traffic light data patterns.

Future examples

A positive example of shared control could be when an integrated exertion system uses movement data to amplify the user’s physical ability. Such as when a wheelchair user spins the wheels, the system could actuate synchronously to the user’s movement to actuate its engine and allow the wheel to spin effortlessly.

A malicious example of shared control could be when an integrated exertion system uses physiological data from the user to communicate that they have reached a state falsely, for example, in communicating to the user that they have reached a peripheral awareness state when the user has not. Since the user does not have a way to tell if this is true, it can lead to a false understanding of one's abilities and potentially limit growth opportunities.

Tactic two: The system acts in real time and affords various user experiences

The integration systems we explored were always in contact with the user's body. However, the data used by the integration system to actuate and how much control the user had over such data was different in each case study. We observed that this control, or lack of control, over the data leads to various user experiences. Here, we present three examples where the system can be experienced by the user as part of their body, as a partner, or as a symbiotic agent - based on the data type and how much control the user has over this data. For example,

1. the system acts in real time to synchronously move with the user’s body to facilitate the user to experience the system as part of their body.
2. the system acts in real time by building from the context of the situation to complement the sensing abilities of the user during the experience.
3. the system acts in real time by reading from the physiological signal of the user to control the system, gaining access to the user’s pre-attentive state to support the experience.

Future examples

A positive example of the system acting in real time could be when an integrated exertion system uses contextual data to assist a bike rider performing a jump to boost the speed required according to the distance and angle of a ramp to jump successfully.

A malicious example of the system acting in real time could be when an integrated exertion system physiological data and this personalised data about the user's pre-attentive processing state is sent to third parties that could charge the user for premium insurance services due to slower than average pre-attentive processing state responses—creating an uneven insurance market for neurodiverse individuals.

Tactic three: The user can gain multiple extended abilities when the system acts

In this tactic, we recommend extending multiple user abilities in combination, such as physical ability to go faster based on the context, and cognitive ability to gain increased perception from timely and instrumental information delivered to the user. For example,

1. where the system extends the user's physical ability, such as by enabling them to go faster, and allows the user to control the system with their body movement rather than using buttons for the user to embody the extra strength.
2. where the system extends the user's cognitive ability to gain increased sense-making in relation to the activity, to invite the user to fluidly adjust their actions to work in a partnership with the system.
3. where the system extends the user's cognitive ability to gain increased perception in relation to previously difficult to perceive or imperceptible information to help the user to "tune in" and expand their perceptual awareness.

Future examples

A positive example of when the user gains multiple extended abilities could be when an integrated exertion system provides timely actionable cues for increased awareness in an encouraging way. To encourage the user to exert and push their limits, the system actuates its engine support if the rider does not quite reach the target to create a safe environment where the rider can push their limits.

A malicious example of when the user gains multiple extended abilities could be when an integrated exertion system supports, for example, increased strength to go faster while also overloading the user cognitively with meaningless information, causing an increased cognitive load and making it challenging to navigate a time-critical environment such as a street with vehicles and traffic lights.

Tactic four: Designing to elicit trust from the user to promote integration

We provide three examples where the functionality of the system contributes to building up the user's trust of the system to facilitate integration. For example,

1. the user has overriding control over the system to gradually adjust to the system acting in the experience and build an understanding of how the system works.
2. the system turns the interpreted data into ad hoc cues that the user can make sense of and turn into actions to benefit; over time, the user builds trust in the system through repeated positive reinforcement.
3. the system acts on the experience and focuses on eliciting from the user emotions with positive valence like joy and delight, as these can afford the user an opportunity to develop trust [33].

Future examples

A positive example of an integrated exertion system that elicits trust from the user could be when the system consistently and timely delivers instrumental information that the user can act on and benefit from in the context of the experience.

A malicious example of an integrated exertion system that elicits trust from the user could be when the system changes the way it acts during a potentially dangerous environment, such as going downhill.

Tactic five: The user's extended corporeal awareness can be used as a design resource in integrated exertion experiences

Consider the user's extended corporeal awareness as a design resource that the system can alter to facilitate different integrated exertion experiences. For example,

1. the user's corporeal awareness remains extended to include the system, when the user embodies the control of extra engine support synchronously with their body movements.
2. the system acts on the experience by using contextual data and reveals itself out of the user's extended corporeal awareness, drawing a division between the user and the system, and strengthening the experience of working with a context aware partner.
3. the system acts on the experience by using physiological data and the experience of the extended corporeal awareness can be strengthened by facilitating a kinetic feedback loop between the user's physiological data as a controller of the system.

Future examples

A positive example of an integrated exertion system that uses extended corporeal awareness as a design resource could be a dance performance to promote self-expression. The system could act synchronously to dance moves to augment an artistic expression.

A malicious example of an integrated exertion system that uses extended corporeal awareness as a design resource could be one in an emergency response situation that limits the user's corporeal awareness so that the user is not aware of rescue equipment reaching high temperatures, leading to burning risk.

This section presented five design tactics with three examples each, based on the three different data types. We then offered a positive and malicious application of the tactics to conceptualise future integrated exertion systems. We believe that contrasting both possibilities of how integrated exertion can evolve is critical as we begin to shape integrated exertion as a design space across many other exertion experiences to consider ethical choices that steer us towards a desirable future. Through this contrast, we promote a values-oriented approach where more people can benefit from integrated exertion experiences regardless of body shape, size, age, and neurodiverse differences [35,68,69]. Ultimately, our work offers the integrated exertion framework and the accompanying design tactics as ways to promote healthy and exciting engagement with technology.

7.4 Control negotiation moments in integrated exertion and the user's agency

A sense of agency has been defined as "the feeling of controlling one's own actions and, through them, events in the external world" [46]. In interaction, traditional input and output paradigm examples are often characterized by experiences where the users exclaims: “It must have been me who just pressed this button” [22]; and “I did that!” [15]. The sense of agency has been explored in HCI works [14,15,28,49] as machines are becoming increasingly capable of participating in the user experience as partners. Such as in the integration paradigm, where the system can participate without user input to generate an output [37]. This active participation affects our sense of agency when merged with a machine in integrated exertion. Because the user might have control, semi-control, or no control over the data used by the system to perform an actuation resulting in varying degrees of user-system control negotiation moments.

The sensation of control is complex in integrated exertion, and it can be influenced, studied, and further developed conceptually through the tactics we presented. In particular, using tactic two, concerned with "when the system acts in real-time", and tactic five, concerned with "user’s extended corporeal awareness as a design resource". For example, the user's corporeal awareness can be extended to include the integrated exertion system when synchronously actuating to the user's movements as a continuous extension of their initiated actions [11]. When the system uses external data, not controlled by the user, to determine when and how much to actuate, the actuation causes the user to adjust to the non-user-initiated actuation and its effect in the external world. While this can break the experience of being integrated with the machine, it offers the user an experience of being with a participating partner that can support the user's goals. Lastly, when the data is semi-controlled by the user, as is the case with physiological data, the experience of agency can be extended to offer kinetic feedback about physiological states not easily sensed by the user, resulting in being able to perceive one's physiological states through changes in the experience of agency mediated by the system's actuation.

While our work offers an initial understanding of the effects of how much control a user has over the data used by the system to perform an actuation and the link to the user's experience of agency in integrated exertion. Further work is needed to explore user-system control negotiation moments in an integrated exertion context considering the machine type and its actuation, the navigation of the environment in which integrated exertion occurs, and the evolving user's and machine's abilities for fluid adjustability in control negotiation moments.

8 LIMITATIONS AND FUTURE WORK

We acknowledge various limitations in our work around the case studies. Further insights could have been derived if participants had the prototypes for longer, the prototypes had been studied in different traffic conditions, participants had cycled for longer distances, and had we invited more participants. Our recruitment criteria were designed to target a diverse range of participants across age, gender and cycling experience. We recognise that our systems were evaluated with what are considered healthy individuals. In the future we would like to explore how integrated exertion systems can support different bodies, whether people with permanent or temporary impairment (injury). This exploration may offer more user experience insights to enrich the framework.

Our work uses eBikes as they allow the user to invest physical effort while we can modify the electric engine to actuate based on different data types. We are wondering if other systems could allow the user to invest physical effort to exert, such as cycling, to study integrated exertion experiences? Future work could explore, for example, Segways [88] which allow leaning sideways, eSkates [109] that can be used in combination with user kicks to accelerate, and eWheelchairs [94] used in combination with arm movement to spin the wheels to further explore the user experiences and tactics presented in the integrated exertion framework beyond eBikes. For example, we could envision designing an integrated exertion “partner” using an eWheelchair that dynamically adjusts engine support according to the floor's inclination, resulting in a co-operative experience.

All our prototypes were evaluated in an urban context. Future work could also explore other environmental contexts such as mountains (through, for example, electric mountain bikes), the aquatic domain (through, for example, surfboards with electric engines [116]), or air-based experiences (through, for example, motor-powered paragliding [116]). This work could complement our framework with an enriched understanding of the opportunities and limitations of the coming together of the exerting body and the environmental context.

We also acknowledge that we only explored three different data types (movement, contextual and physiological data). In this respect, we have only begun to explore the possible data types that could inform integrated exertion experiences. In future work, one possible additional data type to explore could be the position of other bodies in relation to the exerting body. In personal, social and public situations, the proximity of other bodies to the user’s body differs and this results in different experiences [27,54]. Interestingly, this proximity can offer a new data type from which integrated exertion systems can draw. For example, researchers could consider the social experience that occurs when other bodies join the exertion experience. For example, a crowd’s proximity and their cheering could serve as a data type to increase engine support in a system to support the exerting user.

9 CONCLUSION

We have presented a conceptual framework for understanding and designing integrated exertion experiences - where computing machinery tightly coupled with the human body can act on the experience to extend the user's abilities while creating user-system control negotiation moments. Our objective with this framework was to synthesize the learnings from designing, building and studying three integrated exertion systems that each used a different data type (movement, contextual, physiological data) to "act" on the experience and resulted in various integrated exertion user experiences. The framework and accompanying design tactics can inform designers and researchers how to study and create integrated exertion experiences. In addition, we presented positive and malicious integrated exertion future examples to invite reflections to construct and promote healthy and responsible engagement with technology.

The three prototypes that informed the integrated exertion framework reveal the varying degree of user-system control negotiation depending on the data type used by the system to act. This provides opportunities to study and create integrated exertion systems for playful engagement, such as sports, social exertion, and for work, such as for emergency response situations where exertion occurs while working with technological equipment outdoors to attend to a situation.

We conclude by providing three recommendations about how other designers and researchers can benefit from the framework, tactics and futures presented in this work.

Human-machine control negotiation moments offer opportunities to rethink interaction conventions where "control" has been an indisputable ethos for designing computing machinery [14,71,91]. We showed that human-machine negotiation control moments arise when the machine acts to extend the user's abilities to support a goal. This is a rich and complex, user, place, social and technological interdependent situation that designers and researchers need cautiously explore to identify user acceptable control negotiation boundaries while ethically extending the user's abilities.

The twelve integrated exertion experiences and the five design tactics with examples for each of the three data types could be applied to land, water, and air exertion systems to explore the friction between adapting to user-machine control negotiation moments and having one's abilities extended or challenged. Ultimately to extend design knowledge across different terrains and support more users enjoying physical activity.

The interaction to integration passage in integrated exertion is vividly displayed. The participating machine challenges the user's conventional control experience. Here, designers and researchers can draw from the tactics presented to design for user-machine "adaptiveness", where performative adaptation occurs as both the user and machine become more accustomed to one another through practice.

Finally, we identified that design knowledge to study and design integrated exertion is nascent today, and with the framework, tactics and futures presented, we contribute to extending the needed understanding to guide designers and researchers to study and design integrated exertion experiences.

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