From Biological to Digital Organs: A Design Space for Human-Machine Integration

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It's not a new concept to combine technology with the human body. In light of technological breakthroughs, increased real-world deployments, and expanding ethical and societal ramifications, it is pivotal to comprehend how integration technology will influence user interaction. Moreover, when we shift from the familiar perspective of human-computer interaction to views of human-computer integration or augmentation that are still developing, new research topics and design alternatives emerge. In this paper, we propose the idea of devices becoming "digital organs" that act on the boundaries of conscious attention. We discuss a design space that attempts to map the parameters governing the design of bodily integration systems, as well as directions to create appropriate experiences.

CCS Concepts: • **Computer systems organization** → **Embedded systems**; *Redundancy*; Robotics; • **Networks** → Network reliability.

Additional Key Words and Phrases: augmentation; muscle simulation and actuation; bodily interactions

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1 INTRODUCTION

Interactive computing systems with sensory fusion technologies, can eliminate the strict boundary (in form of displays and input devices) that distinguishes humans from machines, and through bio-sensing (e.g., skin conductance, heart rate, brain potentials, and so forth), can understand the user's implicit, precognitive demands. This type of physiological sensing and output allows systems to infer users' states in addition to health-related applications (e.g., task engagement, anxiety, workload, and so forth) and act accordingly. A variety of strategies have lately emerged that can also boost physiological activity (e.g., electrical muscle stimulation, galvanic vestibular stimulation, transcranial stimulation). This essentially allows HCI researchers to create new forms of interactive system that directly reads and controls the user's body.

The line between physiological and computing mechanisms has become more blurred as a result of on-body and wearable gadgets. These systems extend the experienced human body and are perceived through embodiment. There are implanted devices [7], ingested devices [12], or epidermal electronics [21], as well as devices which extend or manipulate the body [23], or stimulate mid-air sensation [22]. Sensor miniaturization has resulted in commercial wearables that monitor and interpret physiological inputs, such running bracelets, sleep trackers, and heartbeat watches, in addition to

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advanced in-lab setups. To name a few examples, glasses (e.g., Google Glass), shoes (e.g., Adidas GMR Play Connected), armband (e.g Myo Gesture Control) and jewelry (e.g., Oura) that have proximal and persistent touch with our skin have enabled computing systems to sense and reconstruct our physiological activity. Nonetheless, due to a number of outstanding constraints in the field, these systems remain isolated examples.

The user and the technology could form a tightly coupled system to appropriately comprehend and co-shape the interaction within a larger physical, digital, and social context. In order for these systems to work in tandem with people, they must have some level of autonomy that must be coordinated with the user. To progress on the path of better integration between users and technology, we propose the concept of ""digital organs" – Identical like your organs, which do not require your conscious control. Also, these system's real-time feedback must also be in sync with the user's experiences. Imagine the idea of monitoring battery status of integrated devices as "digital organ": instead of deliberately checking the battery status, you could feel it in your body as dehydration or heat exchange and thereby receive the signal implicitly. It's analogous to having "digital organs", which work similarly to real organs in terms of sensing and actuation, resulting in a strong sense of embodiment.

There are many open challenges in the field specially when it comes to striking a balance between precise sensing/ actuation, longevity of usage, feedback modalities and user experience. A more collaborative and holistic approach is needed in order for the field to mature. Our work highlights factors and challenges that may affect the design, user experience and acceptance of physiological input/ output systems, particularly the agency's experience. Our key contribution is an understanding of the relationship between particular characteristics and related user experience. We argue that a deeper knowledge of the relationship between physiological input/output system characteristics and associated user experience would provide a solid foundation for future applications.

2 BACKGROUND

The concept of system-user integration can be found in the history of computing, art, philosophy, neuroscience, and even science fiction. Closed-loop machine systems were inspired by Norbert Wiener's cybernetics movement, and examples of devices integrating with the user's body can be found virtually from the beginning of the field of interactive computing [11]. Licklider's "(Hu)manComputer Symbiosis," based on cybernetics ideas, proposed that "cooperation between users and machines was an expected development," and that this would necessitate a "very close coupling between the human and the electronic member of the partnership," alluding to notions of body-integration [13]."

The bodily "integration" can be viewed from two perspectives : bystander vs. user perspective. Bystanders have a board and indirect view of the system. Users have a more direct and hands-on experience with the system. A man riding a bike, for example, is perceived as a single entity by a bystander, whereas the man on the bike is aware of the distinction. Whereas skin-worn sensors [25] fostering direct and discreet interaction could be perceived as a single entity by both bystander and the user. Consequently, we ask: *How can we design technologies in which humans and machines are indistinguishable, not just from the standpoint of bystanders, but also from the human's own perspective?*

Wearables today are typically constructed with a rigid form factor that limits their positioning on the user's body. As a result, they have restricted access to information and are not effectively integrated into the body. Flexible and stretchable electronics are being used in epidermal electronics and interactive textiles, allowing for stronger fusions with the human body, such as electrical muscle stimulation (EMS). EMS can be used to convey object affordances [16], initiate direct user movements [14, 15], or to provide haptic feedback [17], by varying stimulus characteristics (e.g., amplitudes, pulse widths, and frequencies). The essential distinction between a movement accelerated by muscle actuation technology and one that is not (e.g., during voluntary training) is the absence of agency experienced, i.e., the user is moved by the system rather than being self-propelled [10]. This might be a major roadblock to widespread adoption of such technologies as they bypass the cognitive system, negatively affecting user experience. As a community we need to tackle the question of *'How can we design physiological input/ output interactions to preserve a high sense of agency?'*. We identify the following gaps and challenges in knowledge for further investigation.

3 A DESIGN SPACE FOR INTEGRATED INPUT/ OUTPUT SYSTEMS

To elucidate the design space, we leaned on the three dimensions of physiological input/ output systems i.e., perspective on the y-axis and interaction to integration and feedback modality on the x-axis as shown in Figure 1. The far left and far right of the x-axis indicate explicit and implicit feedback. Similarly, the top-end and bottom-end of the y-axis indicate bystanders and users, respectively. The gradient backdrop representing the transition from interaction to integration, which conveys the blurriness between the systems. Unobtrusive feedback that is abstract in nature is referred to as implicit feedback [8]. Clear and explainable feedback in the form of visuals or audio alongside haptic feedback is referred to as explicit feedback [1].

The Motion Echo Snowboard [19] is a technology that helps snowboarders learn to balance their body weight. It has been developed to display LEDs on the board, which snowboarders must interpret and learn about how effectively they are balancing their weight by looking down. Juggling in VR study uses virtual balls, audio and controller's in-built haptic actuators as a form of sensory substitution [2]. They provide the user with explicit feedback. Exoskeletons [20], muscle simulation [15], and transdermal technologies [6, 26] are all moving in the direction of more implicit feedback. Deep implants, such as pacemakers or cerebral shunts [3], and pass-through technology [5], on the other hand, are fully implicit.

As the technology matures and applies to various domains, we predict that existing design criteria (e.g., safety) will have to co-adapt with other factors (e.g., form factor, modality, user and task needs). There is minimal clear precedent for the interaction challenges that arise from operating just beneath or just above the user's awareness, as well as just ahead or just behind the user's intent [18]. We suggest that shared understandings and methodologies be developed for designing, developing, refining, testing, and assessing systems that interact directly with the body, specially operating on a ""digital organs" paradigm.

3.1 Sense of Agency

Such interfaces, from a philosophical standpoint, raise the basic question of who is accountable for an action, as they may interfere with a person's free will. It's crucial to determine what parts of the system should be provided with agency and to what extent. It must be designed in such a way that the technology acts as an extension of the body while displaying minimal or no autonomous behavior at which one can interact in a reflexive manner. While the question of agency is a major challenge for physiological input/ output, we argue it is also a design opportunity.

This problem can be overcome from a neurobiological standpoint. Intentional binding provides us with a tool from neuroscience for evaluating these phenomena quantitatively [4]. However, we find that the design space is not yet well understood as more and more interfaces find new configurations for shared agency [9]. A design framework might therefore be useful to guide designers regarding both, where and how to endow a system with agency.

3.2 User Acceptance

One of the most critical factors in determining whether technology succeeds or fails is user acceptance [24]. The comparison of overall experience to task immersion is a intriguing area to pursue in order to better understand the

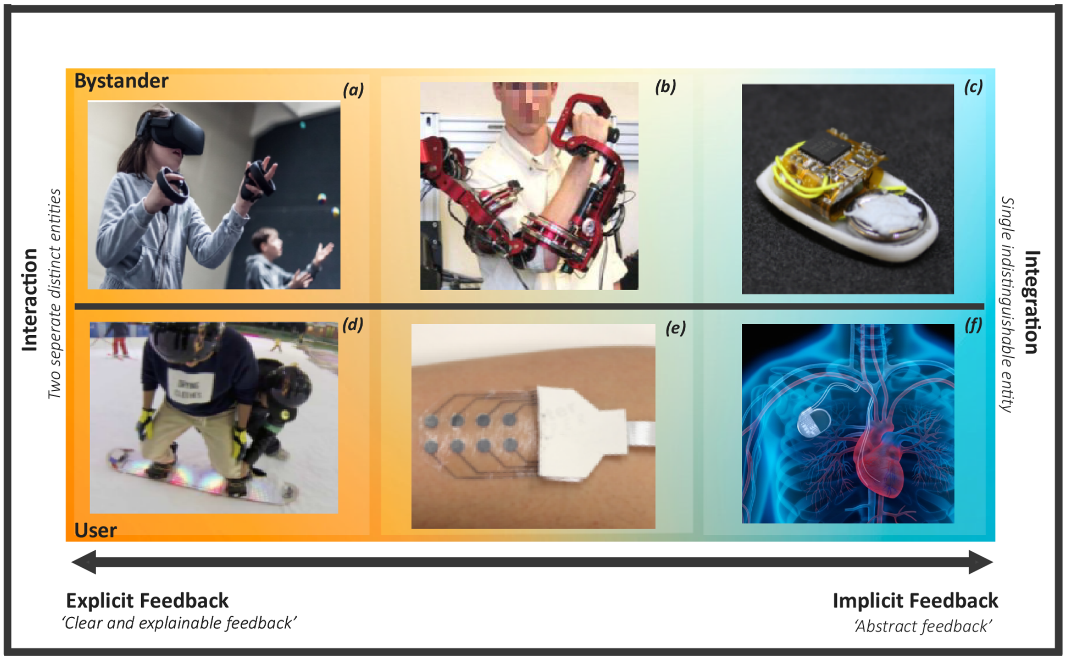

Fig. 1. Some examples of Physiological input/ output systems placed across our framework: a) Juggling in VR [2] b) Exoskeleton [20] c) ChewIt [5] d) Motion Echo Snowboard [19] e) Tacttoo [26] f) Pacemaker [3]

overall appropriateness of such systems as a physiological input/ output paradigm. *Is such a technology too obstructive to be considered a viable HCI paradigm?* Our group conducted a user study to capture users' feedback on the acceptance of EMS technology. We derived four EMS-based interaction scenarios that differ along the dimensions of Controllability, Intrusiveness, Continuity, Safety-criticality and Bi-directionality. Users were apprehensive about giving up control, and long-term exposure and intrusive nature were rejected. Consequently, balancing between locus of control as well as (sub)conscious in- and output will be a key issue to realize human-machine symbiosis in form of "digital organs".

4 CONCLUSION

We discovered that physiological input/output systems are designed in a variety of ways, which could make comparison, evaluation as well as conceptualizing the design space, difficult. In this paper, we present a design space that aids in the design process and allows for better communication of ideas through a shared understanding. The key questions we ask are *'How can we create technology that blur the lines between humans and machines while maintaining a sense of agency?'* and *'How far should a machine go in an attempt to understand a human in real time?'*. We have discussed about the advantages of using an integration lens, but it's also important to consider the potential risks. For example *'How will conflict resolution take place in such an integrated scenario if human goals differ from machine goals in a certain scenario?'*. Our goal is to assist HCI researchers in developing integrated systems that allow users to do sensory-motor activities without having to think about their actions. To sum up, we are thrilled about the field's potential and how it will influence how people interact with technology, and we would welcome feedback on the concept of "digital organs" emerging in discussions at the proposed workshop.

REFERENCES

[1] Jack A Adams. 1971. A closed-loop theory of motor learning. *Journal of motor behavior* 3, 2 (1971), 111–150.

[2] Jindřich Adolf, Peter Kán, Benjamin Outram, Hannes Kaufmann, Jaromír Doležal, and Lenka Lhotská. 2019. Juggling in vr: Advantages of immersive virtual reality in juggling learning. In *25th ACM Symposium on Virtual Reality Software and Technology*. 1–5.

[3] RR Brownlee, JB Shimmel-Golden, CJ Del Marco, and S Furman. 1982. A new symbolic language for diagramming pacemaker/heart interaction. *Pacing and Clinical Electrophysiology* 5, 5 (1982), 700–709.

[4] David Coyle, James Moore, Per Ola Kristensson, Paul Fletcher, and Alan Blackwell. 2012. I did that! Measuring users' experience of agency in their own actions. In *Proceedings of the SIGCHI conference on human factors in computing systems*. 2025–2034.

[5] Pablo Gallego Cascón, Denys JC Matthies, Sachith Muthukumarana, and Suranga Nanayakkara. 2019. Chewit. An intraoral interface for discreet interactions. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–13.

[6] Kayla J Heffernan, Frank Vetere, and Shanton Chang. 2016. You put what, where? Hobbyist use of insertable devices. In *Proceedings of the 2016 CHI conference on human factors in computing systems*. 1798–1809.

[7] Christian Holz, Tovi Grossman, George Fitzmaurice, and Anne Agur. 2012. Implanted user interfaces. In *Proceedings of the SIGCHI conference on human factors in computing systems*. 503–512.

[8] Gawesh Jawaheer, Martin Szomszor, and Patty Kostkova. 2010. Comparison of implicit and explicit feedback from an online music recommendation service. In *proceedings of the 1st international workshop on information heterogeneity and fusion in recommender systems*. 47–51.

[9] Shunichi Kasahara, Jun Nishida, and Pedro Lopes. 2019. Preemptive action: Accelerating human reaction using electrical muscle stimulation without compromising agency. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–15.

[10] Shunichi Kasahara, Kazuma Takada, Jun Nishida, Kazuhisa Shibata, Shinsuke Shimojo, and Pedro Lopes. 2021. Preserving agency during electrical muscle stimulation training speeds up reaction time directly after removing EMS. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. 1–9.

[11] Kevin Kelly. 2009. *Out of control: The new biology of machines, social systems, and the economic world*. Hachette UK.

[12] Zhuying Li, Felix Brandmueller, Stefan Greuter, and Florian Mueller. 2018. The Guts Game: Designing Playful Experiences for Ingestible Devices. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–1.

[13] Joseph CR Licklider. 1960. Man-computer symbiosis. *IRE transactions on human factors in electronics* 1 (1960), 4–11.

[14] Pedro Lopes and Patrick Baudisch. 2017. Interactive systems based on electrical muscle stimulation. *Computer* 50, 10 (2017), 28–35.

[15] Pedro Lopes, Alexandra Ion, Willi Mueller, Daniel Hoffmann, Patrik Jonell, and Patrick Baudisch. 2015. Proprioceptive interaction. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 939–948.

[16] Pedro Lopes, Patrik Jonell, and Patrick Baudisch. 2015. Affordance++ allowing objects to communicate dynamic use. In *Proceedings of the 33rd annual acm conference on human factors in computing systems*. 2515–2524.

[17] Kevin Lu and Aarnout Brombacher. 2020. Haptic Feedback in Running: Is It Possible for Information Transfer through Electrical Muscle Signalling?. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction*. 479–485.

[18] Florian Floyd Mueller, Pedro Lopes, Paul Strohmeier, Wendy Ju, Caitlyn Seim, Martin Weigel, Suranga Nanayakkara, Marianna Obrist, Zhuying Li, Joseph Delfa, et al. 2020. Next steps for human-computer integration. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–15.

[19] Hyung Kun Park and Woohun Lee. 2016. Motion echo snowboard: enhancing body movement perception in sport via visually augmented feedback. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems*. 192–203.

[20] Joel C Perry, Jacob Rosen, and Stephen Burns. 2007. Upper-limb powered exoskeleton design. *IEEE/ASME transactions on mechatronics* 12, 4 (2007), 408–417.

[21] Jürgen Steimle. 2016. Skin–The Next User Interface. *Computer* 49, 4 (2016), 83–87.

[22] Paul Strohmeier, Sebastian Boring, and Kasper Hornbæk. 2018. From Pulse Trains to" Coloring with Vibrations" Motion Mappings for Mid-Air Haptic Textures. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–13.

[23] Dag Svanaes and Martin Solheim. 2016. Wag your tail and flap your ears: The kinesthetic user experience of extending your body. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. 3778–3779.

[24] Viswanath Venkatesh, Michael G Morris, Gordon B Davis, and Fred D Davis. 2003. User acceptance of information technology: Toward a unified view. *MIS quarterly* (2003), 425–478.

[25] Martin Weigel, Tong Lu, Gilles Bailly, Antti Oulasvirta, Carmel Majidi, and Jürgen Steimle. 2015. Iskin: flexible, stretchable and visually customizable on-body touch sensors for mobile computing. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 2991–3000.

[26] Anusha Withana, Daniel Groeger, and Jürgen Steimle. 2018. Tacttoo: A thin and feel-through tattoo for on-skin tactile output. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*. 365–378.