Neuro-Skin: A Novel Paradigm for On-Body Interactive Computing

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This paper discusses the integration of technology with the human body through on-body devices. Current wearable technology is limited by its rigid structure, making it challenging to place in specific areas of the body. However, the development of flexible and stretchable electronics is allowing for more effective integration with the human body. "Neuro-skin" is a proposed concept that combines neurology and skin to offer real-time feedback to the body, enhancing our ability. Design guidelines are essential to develop on-body technology that meets the needs of users, and wearability is a crucial factor to consider. The wearability criteria include technological requirements, sensorimotor activity, human abilities, social interactions, and inclusivity. Different perspectives, such as technology-centered, sensorimotor, human abilities, social, and inclusivity, are discussed to consider the human body's interaction with on-body technology. The goal is to design on-body technology that is easy to use, comfortable, socially acceptable, and accessible to everyone, regardless of age, gender, ability, or cultural background.

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

Additional Key Words and Phrases: sensory fusion, bio-sensing, physiological monitoring, body-based technology, neuro-skin, electric muscle stimulation, material-enabled technology, electronic textiles

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1 INTRODUCTION

Interactive computing systems that use sensory fusion technologies can blur the distinction between humans and machines by eliminating strict boundaries in the form of displays and input devices. By utilizing bio-sensing techniques such as skin conductance, heart rate, and brain potentials, these systems can comprehend users' implicit and precognitive demands. This type of physiological sensing allows these systems to understand users' states and to respond accordingly. Additionally, this technology has health-related applications, such as assessing task engagement, anxiety, and workload. New strategies have recently emerged that can enhance physiological activity, such as electrical muscle stimulation, galvanic vestibular stimulation, and transcranial stimulation. These approaches enable researchers in human-computer interaction to develop new interactive systems that can directly monitor and manipulate the user's body.

With advancements in sensor technology, it is now possible to produce wearables that can monitor and interpret physiological inputs. This includes popular devices like running bracelets, sleep trackers, and watches, as well as sophisticated in-lab setups. Examples of these devices include glasses like Google Glass, shoes like the Adidas GMR Play Connected, armbands such as Myo Gesture Control, and jewelry like the Oura ring. These devices have the unique ability to detect and reconstruct our physiological activity by maintaining persistent contact with our skin. There are implanted devices [6], ingested devices [9], or epidermal electronics [19], as well as devices which extend or manipulate the body [21], or stimulate mid-air sensation [20]. Additionally, smart home devices like voice assistants and smart lighting can incorporate touch-based interactions, such as gestures or pressure-sensitive surfaces, to enable more intuitive and seamless control of the home environment. These technologies have the potential to enhance our sensory experiences and create more immersive and engaging interactions with the world around us, whether through tactile feedback, visual displays, or other forms of multisensory stimulation. To ensure that the use of technology is practical and beneficial, it is important that the effort required to use the technology does not outweigh its benefits. Therefore, it is essential to consider how these technologies can be made wearable and convenient for everyday use so that people can easily integrate them into their daily routines. This means that there should be a greater focus on developing wearable technologies that are comfortable, user-friendly, and fit seamlessly into people's lifestyles, without causing any undue burden or inconvenience.

Electric Muscle Stimulation (EMS) is a popular input-output modality in HCI, allowing the computer to control the user's physical movements by stimulating muscle contractions through surface-based electrodes [11, 12]. While EMS presents opportunities in conveying information, improving performance, and creating bidirectional communication channels between user and machine, achieving fine-grained control through EMS remains a challenge [15]. Existing HCI literature primarily focuses on stimulating the forearms and biceps to drive rotations around the wrist and elbow, but research suggests that more complex movement patterns can be achieved through increased electrode complexity [2, 14]. However, with increasing numbers of electrodes, the benefits of individual electrodes are quickly outweighed by the difficulty in deployment and calibration. Thus, researchers need to rethink the use of electrodes to achieve greater control with minimal effort. Skill-Sleeves, for example, requires a strong connection to the body and have a large number of components that demand careful garment layout and cable management [8]. In addition to wearability, factors such as deployability, customization, and manufacturing should also be considered when designing material-enabled body-based technology.

To progress on the path of better integration between users and technology, we propose the concept of "Neuro-skin", a technology that combines elements of neurology and skin. The surface of our skin is equipped with tiny, interconnected sensors and actuators that can detect and respond to a wide range of stimuli. This neuro-skin technology has the potential to detect and interpret various stimuli including temperature, pressure, and humidity, providing a comprehensive understanding of our surroundings. By offering real-time feedback to the body, this technology can assist in enhancing our ability. There are many open challenges in the field specially when it comes to striking a balance between precise sensing/ actuation, the longevity of usage, feedback modalities, and user experience. A more collaborative and holistic approach is needed in order for the field to mature. 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 building future applications.

2 BACKGROUND

The idea of integrating systems with users has been present throughout various fields such as computing, art, philosophy, neuroscience, and science fiction. The concept of closed-loop machine systems was derived from Norbert Wiener's cybernetics movement, and there have been instances of devices integrating with the user's body since the early stages of interactive computing [7]. Licklider's concept of "(Hu)man-Computer Symbiosis," which was based on cybernetics principles, proposed that the cooperation between users and machines would inevitably require a close coupling between humans and electronic members of the partnership, suggesting the integration of the body with technology [10]. Currently, wearables are typically designed with a rigid structure, which limits where they can be placed on the body, resulting in restricted access to information and limited integration with the human body. However, with the use of flexible and stretchable electronics, epidermal electronics and interactive textiles are being developed to create stronger connections with the human body. This allows for more effective integration of wearables with the human body, providing new opportunities for monitoring and interaction. 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?*

One way to integrate electronics into clothing is to attach conventional electronics to the fabric. The FLORA ecosystem, based on the Arduino LilyPad, is an example of this approach. It involves attaching rigid electronic development boards with microcontrollers, LEDs, and other components onto soft textiles. However, there is a trend in wearable computing to move towards offloading functionality into the fabric itself, allowing for more complex and customizable clothing [3, 17]. Techniques like embroidery, weaving, and knitting have been used to create fabrics with specialized properties like piezo-resistive or piezoelectric behavior, and chemical treatments and functional dyes have been used to embed electrical functionality into textiles [13, 16, 18]. By combining these approaches, it's possible to create fabric objects, accessories, and full garments with complex electronic functionality. We can draw inspiration from designs presented by Freire, who incorporates materials and methods typically used in sports garments and sneakers manufacturing, such as layering and bonding multiple materials to achieve desired functionality [1, 3**?** , 4].

As wearable technology becomes more prevalent, the importance of wearability as a desirable feature is increasing. As a result, there is a growing amount of research dedicated to investigating the wearability of specific devices and wearability in general. Zeagler et al. is a useful starting point for exploring this area [22]. The study of wearability comes from various perspectives, including the identification of wearability criteria based on user preferences. To design highly integrated textile devices that are wearable, it is important to consider various perspectives, such as technological requirements, general human sensorimotor activity, specific human abilities, and human social interactions [5]. Clustering design guidelines based on these perspectives can be useful for creating wearable technology that meets the needs of users.

3 A DESIGN FRAMEWORK

The following design guidelines can be utilized to develop a plan for designing Neuro-skin from five perspectives:

- Technology-centered perspective: This approach looks at whether the technology can work as intended. It focuses on getting the most accurate information possible and making sure the technology is placed in the best location on the body to achieve maximum functionality. For instance, an EMG electrode must have good contact with the skin to detect muscle movements. Also, when designing a wearable EMS device, it is crucial to consider the placement of the electrodes on the body to ensure effective muscle stimulation and user comfort.
- Sensorimotor perspective: This perspective looks at the human body in two ways: psychophysical and biomechanical. Psychophysical approaches aim to make the on-body device as easy to use as possible, while biomechanical approaches take into account the device's shape and how it interacts with the body. To be wearable, a device must not limit natural movements, distribute weight evenly, and be easily accessible. It is important to remember that people come in many shapes and sizes.

- Human abilities perspective: This approach considers how humans interact with on-body technology. To assess human performance, we might ask where on the body a user can best respond to notifications, or where to place the device for quick and easy access. We also need to investigate how on-body technology can make it easier for users to input/ output information.
- Social perspective: On-body technology are both intimate and social, affecting how the wearer perceives themselves and how they are perceived by others. Social acceptability is an increasingly important issue in human-computer interaction. To make it more comfortable, intuitive, and socially acceptable, we must consider both the aesthetic and social aspects of the device.
- Equal access and inclusivity perspective:It is crucial to consider equal access and inclusivity when designing on-body technology. Inclusivity means designing devices that can be used by everyone, regardless of age, gender, ability, or cultural background. Equal access means that devices should not create additional barriers for individuals with disabilities, and they should be able to use the device as independently as possible. For example, wearable devices should have alternative input methods for individuals with motor impairments, such as voice control or switch access.

4 CONCLUSION

The concept of integrating technology with the human body has been around for a while, with wearables being designed to connect more closely with the body. Current on-body technology is limited by its rigid structure, which makes it challenging to place it in specific areas of the body. However, flexible and stretchable electronics are being developed, allowing for more effective integration of wearables with the human body. To design wearable technology that is indistinguishable from the human perspective, the fabric itself is being used to embed electrical functionality, allowing for complex and customizable clothing.The concept of "Neuro-skin" is proposed, combining elements of neurology and skin to offer real-time feedback to the body, which can enhance our ability. Design guidelines are essential to develop on-body technology that meets the needs of users, and wearability is a crucial factor to consider. Wearability criteria include technological requirements, sensorimotor activity, human abilities, social interactions, and inclusivity. From a technology-centered perspective, the focus is on ensuring that the technology works as intended, and the most accurate information is collected. The sensorimotor perspective considers the human body from psychophysical and biomechanical approaches to make the device easy to use, comfortable, and accessible. The human abilities perspective considers how humans interact with on-body technology and investigates how technology can facilitate input/output information. From a social perspective, the aesthetic and social aspects of the device are considered to make it more comfortable, intuitive, and socially acceptable. Lastly, equal access and inclusivity perspective is vital to ensure that wearable technology is designed to be used by everyone, regardless of age, gender, ability, or cultural background, without creating additional barriers.

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